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NUCLEAR INSTRUMENTS

A JOURNAL ON ACCELERATORS, INSTRUMENTATION AND TECHNIQUES IN NUCLEAR PHYSICS

EDITOR K. SIEGBAHN - UPPSALA

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NUCLEAR INSTRUMENTS

A journal on accelerators, instrumentation and techniques in nuclear physics

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Books for review should be sent to Professor Siegbahn.

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EDITOR'S NOTICE

Nuclear Instruments, like its sister journal *Nuclear Physics* (editor: L. Rosenfeld) is entirely international in character; the editorial board consists of representatives from many different countries.

Apart form the fact that it is convenient to concentrate as much as possible of nuclear instrumentation into one journal, it will also be possible to include more complete descriptions of the various instruments, their theory and their possible applications. Without doubt, much of what is achieved in experimental nuclear physics today is dependent on the present state of techniques. For example, improvements in millimicrosecond pulse technique or the refinement of bubble chambers open up the possibilities of new and interesting experiments; new types of accelerators or improvements of energy analyzing devices reveal new fields of great theoretical significance.

Such information, though often of decisive importance, is frequently hidden in the form of rather sketchy introductions to various papers; this is due to the necessity of concentrating the discussion to the particular scientific problem under investigation.

Since the proposed journal will deal entirely with nuclear instrumentation and related topics it will be possible to make room for more complete papers in this field.

With such an emphasis I believe that the new journal will serve a real purpose. Many nuclear scientists are devoting much of their research work to improvements of nuclear apparatus, techniques, accelerating machines etc.

Nuclear Instruments will offer opportunities for these physicists to give much more complete accounts of their work.

Nuclear Instruments will publish experimental, theoretical and technical articles on subjects such as: accelerators, counters and detectors of nuclear radiation, isotope separators and mass spectrometers, instruments for nuclear spectroscopy, electronic equipment used for nuclear instrumentation and automation and other various miscellaneous nuclear techniques such as dosimetry and instruments used in tracer techniques, etc. Survey articles, short notes and book reviews will also be included.

KAI SIEGBAHN

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THE CERN SYMPOSIUM 1956 (I)

J. B. ADAMS

Cern, Proton Synchrotron Division

Received 8 September 1956

Over two hundred physicists and engineers representing nearly all the high energy nuclear physics centres in the world met in Geneva from June 11th to 16th to present papers and discuss the problems of high energy particle accelerators. This formed part of a two week conference arranged by CERN (European Organization for Nuclear Research) under the general heading "CERN Symposium on High Energy Accelerators and Pion Physics", which was held at the Institute of Physics of the University of Geneva.

About eighty papers were submitted dealing with all aspects of accelerators, of which fifty-six were presented during eleven sessions. All the papers submitted together with notes on the discussions during the sessions are recorded in the Proceedings of the Symposium. Preprints of the papers, which were issued to participants before the conference, permitted the discussions to be based on more substantial papers than could otherwise have been presented by the contributors during the short time available during the sessions.

It is the object of this report to present in retrospect a guide to the papers presented and the discussions that took place during the sessions of the first week of the conference.

During the two sessions held on Monday June 11th, the first day of the conference, ideas were put forward for new accelerating machines that would either give very much higher energies than existing machines or the same energies and very much higher intensities. The evolution of accelerators bears some resemblance to that of the larger prehistoric monsters in that the size increases until a better way is found of achieving the same result. The limitation determining this natural selection has usually been a financial one. The synchrocyclotron design was followed until, for machines in the 600–700 MeV energy range, the cost of the circular magnet became prohibitive. To reach still higher energies, the proton synchrotron design, employing a cheaper form of annular magnet, was exploited. At still higher energies, above 10 GeV, even the annular magnet became too expensive and a variant of the proton synchrotron, namely the alternating gradient proton synchrotron, using an annular magnet of much smaller cross-section, was developed. Machines of this type may well be built to accelerate particles up to 100 GeV if methods of beam control and magnet alignment are sufficiently developed. Already two machines of this type are being constructed for an energy range 20–30 GeV and several higher energy machines are being considered. This progress has been the straight forward evolution of a species.

At this conference, several new species were introducted. All the accelerators mentioned above have used iron as the yoke material in the magnet and, due to saturation of the magnet yoke, the highest fields that can be realized in practice are in the range 10–15 Kgauss. However much the cross-section of the magnet is reduced by strong focusing and however clever the automation, the radius of high energy machines using iron yoked magnets must increase at least linearly with energy and even if the magnet costs are kept down, the building costs, particularly for the alternating gradient machines, which need such elaborate foundations, will soon be considered prohibitive. Also most

physicists prefer to circumnavigate their machine in a few minutes rather than in several hours. The Canberra group in Australia was one of the first to break away from the field limitations imposed by magnets with iron yokes and explore the possibilities of large air cored magnets. However, even if the awe-inspiring methods they propose for generating the necessary high currents for their magnet work satisfactorily, a 100 GeV machine would still need a radius of 80 metres and the power consumption would be enormous.

Two groups from the USSR Academy of Science put forward ideas at this first session that might enable magnetic fields orders of magnitude larger than used at present to be realized. Their proposal consists of setting up a toroidal beam of electrons of very high current density, constrained by relatively weak external magnetic fields, and neutralizing this electron beam to a plasma by introducing protons. The consequent constriction of the cross-section of the toroidal beam gives such a high current concentration that magnetic fields of the order of 10^6 gauss in the torus are predicted. With such high fields, an accelerator of 3 metre radius could be made to hold 100 GeV protons in the orbit and the fields always focus the protons. The interest of the conference showed how acceptable such a machine would be. Experiments designed to confirm their extensive theoretical work, which were described at the session, are still at an early stage. The main problems concern the stability of a toroidal plasma (pinch and wriggle instability) and methods of accelerating the protons in the plasma. It was clear that, although no one was expecting rapid confirmation of the principle in all its aspects, the enthusiasm of the theoreticians and the scale of the effort being devoted to the problem would result in notable advances in the next year. Perhaps some cross-fertilization with the plasma work for sustained thermo-nuclear reactions being carried out elsewhere would benefit both projects.

Another idea, many times discussed amongst accelerator physicists since it was first put forward by Wideröe in 1935, was the subject of several papers during this session. If the nuclei in the target onto which the accelerated particles fall could themselves be made to move in the opposite direction to the incident particles, the resulting reactions would be equivalent to letting particles of very much higher energies fall onto a stationary target. The moving target would of course be a beam of accelerated particles and the two beams would be made to collide in some interaction region. This idea has not been followed up in the past due to the small chance of head-on collision of the accelerated particles compared with the collision of particles in either beam with more or less stationary gas atoms and also due to the small absolute collision rates. The American groups of MURA, Berkeley and Princeton proposed schemes using this idea and getting over the background difficulties by storing the beam pulses originating from a primary accelerating machine so that the intensity of the interacting beams would be about 100 times the intensity of normal proton synchrotron beams and by improving the vacuum in the interacting region to minimize gas atom reactions. Although the background reactions with gas atoms still greatly outnumber the desired reactions, it was shown that this ratio can be made usable by setting up the experiments at right angles to the direction of motion of the interacting beams where the background from the reactions with stationary gas atoms will be of low energy and can easily be screened off. Unless the intensity (i.e. pulse repetition rate) of the primary accelerators is very high however, the equivalent "intensity" of such an interacting beam machine is far below the ordinary proton synchrotron intensities; but such a machine does offer the only way open at present of studying reactions in the TeV range (10^{12} eV). For example, an intersecting beam machine using two proton beams each of 25 GeV energy gives reactions equivalent to a 1.25 TeV machine whose beam falls onto stationary target. To reach 1 TeV even with a plasma accelerator would need a machine of 30 m radius and a normal iron cored proton synchrotron of this energy would be 4000 m radius or 25 km round the orbit.

Schemes were put forward for using a single primary accelerator and ring magnets with constant fields in which particles could be stored up until such time as they are allowed to interact in head-on collision. An attractive feature of such a scheme for machine physicists is that the storage rings could be added to an existing or projected machine to increase its energy after the original energy range had been adequately exploited. Another scheme, proposed by the MURA group, used two Fixed Field Alternating Gradient accelerators with a common straight section in which the beams would intersect at the peak energy of the machines.

Several proposals were made for machines of less than 10 GeV energy which would have beam currents of about 100 times the present beam intensities of the Bevatron and Cosmotron. This is an energy range which is just being exploited by the Bevatron at Berkeley and which will also be covered soon by the Russian 10 GeV machine (Synchrophasotron). Strong arguments were made, particularly by the Harwell group, for building such a machine (which essentially produces beams of K mesons and anti-protons not available from lower energy machines) on the grounds that, since it could only come into operation several years after the Bevatron and the Synchrophasotron, it would only extend the experimental facilities of those machines if it produced very much higher beam intensities. The Harwell group described a 6 GeV proton synchrotron design with spiral ridge poles which can be arranged to leave the radial focusing the same as in a conventional synchrotron but to give stronger focusing to the vertical oscillations. With this arrangement, multi-turn injection is possible, thus ensuring a high injected current; the vertical magnet gap, and consequently the magnetic stored energy, is small enough to permit the use of condenser banks resonating with the magnet inductance at a high repetition frequency for the power supply. They hope to achieve about 100 times the present Bevatron intensity which will certainly add to the number of experiments that can be carried out at these energies.

Another lower energy machine design, for a 3 GeV high intensity constant gradient proton synchrotron, also using a condenser bank for energy storage and a high pulse repetition frequency, was described by the Princeton group during the last session on Saturday morning.

It is interesting to observe that Cosmic Ray physics has so far provided the main justification for building accelerators of higher and higher energy in that the Cosmic Ray experiments have indicated the type of particles that can be produced by the machine. The intensity of the Cosmic radiation is just enough to whet the appetite of the experimental physicist while not spoiling it for the wholesome intensities available from the machines. If the Cosmic radiation can be likened to an apéritif, the first wave of machines now appears to have been the entrée. The main course consisting of the high intensity machines is yet to come. There seems at the moment less justification coming from the Cosmic Ray experiments for machines exceeding 50 GeV.

The MURA group presented a summary of their work on the Fixed Field Alternating Gradient machines which seek to provide high intensities in the energy range 20–50 GeV, i.e. the energy range in which "low" intensity machines have yet to be completed. This work included studies on an electron model demonstrating one of their earliest ideas (Mark I radial sector machine). Both the theoretical work and the experimental work showed that his type of machine may well provide the high intensity machines of the future.

The conference, after such a heroic start, then settled down to discuss more detailed problems of the design of accelerators.

The session on Tuesday morning concerned the Transition Energy or Critical Energy observed in machines of the Alternating Gradient type at present being built by the Brookhaven and CERN groups. The Brookhaven group reported on experiments performed on an electron model of their machine which indicated that very little loss of particles would be experienced as the energy of the particles passed through the critical value. However, during the

discussion that followed this paper, it emerged that the Brookhaven results might be presenting a somewhat optimistic view of the situation. Nevertheless, both Brookhaven and CERN seemed confident that, with suitable corrections to the magnetic fields and perhaps the RF amplitude at the Transition Energy, most of the particles could be retained and accelerated to full energy.

The USSR Academy of Science group described a machine design in which the Transition Energy was arranged to occur above the maximum energy of the machine so that there was no problem in crossing any Critical Energy during the accelerating period of the machine. Their design, which is similar in some respects to that of the Mark I Fixed Field Alternating Gradient machine of the MURA group, uses a magnet in which the magnetic field of a number of sectors is opposite in sign to that of the general guiding field. The resulting closed orbit is distorted in such a way that the Transition Energy can be placed above the maximum energy of the machine. Such a scheme, although avoiding the problems associated with the Transition Energy, introduces others that may be equally troublesome as was revealed in the discussion.

Both the theoretical paper presented by CERN on the non-linear effects occurring at the Transition Energy, which are the reason for loss of particles, since in the linear approximation it can be arranged that no particles are lost, and the general theoretical paper presented by the Physical Institute (USSR Academy of Science) group showed that the problem was reasonably well understood and that methods could be developed to overcome most of the particle losses.

On Tuesday afternoon, problems of ejecting particles from synchrotrons and synchrocyclotrons were considered. The Brookhaven group described the ejection system used successfully with the Cosmotron and the USSR Academy of Science group described a scheme they proposed to use on their projected 7 GeV alternating gradient synchrotron. The CERN group presented a paper on particular problems they had studied of an ejection scheme for their 25 GeV synchrotron. The Brookhaven and CERN schemes use an energy-losing target to set up a displaced closed orbit for those particles striking the target. Only the particles striking the target are brought out of the machine; the others remain on their original orbits unperturbed by the field acting on the deflected particles. In this way particles are extracted from the machine over a long period, giving extracted beam pulse lengths most suitable to present day nuclear physics counting apparatus. One important problem that was touched on by several speakers is the optimum design of the ejection system, the transport of particles to the experimental apparatus and the design of the experimental apparatus itself. It is only recently that the same attention has been given to this problem that is customarily given to the acceleration of particles in the machines themselves. By considering that a machine project is not finished until the largest fraction of ejected particles not only leaves the machine but actually passes through the counter telescopes, large increases in the efficiency of utilization of the machine can be achieved, equivalent to increasing the beam current of the machine by orders of magnitude. Clearly much more thought should be given to using the concept of "acceptance" (angle times amplitude) when designing particle transport systems and, for the high energy machines, where the size and cost of simple bending and focusing magnets becomes prohibitive, one would expect to see distributed quadrupole lens systems extending from the ejector of the machine to the experiments, and counter apparatus being designed to have an acceptance matched to the emittance of the beam of particles reaching that apparatus.

The USSR Academy of Science group put forward two different schemes for particle ejection for their 7 GeV proton synchrotron, a pulsed beam deflector scheme, which ejects particles during a single revolution, and an "adiabatic" deflector ejecting particles over many revolutions. The first scheme, which is similar to the pulsed magnetic deflector bar system used originally on the Berkeley 184″ Synchrocyclotron, has the disadvantage of giving a very short pulse which is difficult to use

efficiently with counter experiments. The "adiabatic" ejector does not use the energy-losing target principle of the Cosmotron but relies on parametric resonance, that is an alteration to the parameters of the machine so that the Q value becomes half integral. The betatron oscillation amplitudes about the closed orbit then grow and particles in the region of a previously introduced "hump" in the closed orbit pass into a region in which they can be separated from the circulating beam and ejected. A theoretical efficiency of 10–14% was predicted for this system which is similar to that expected from an energy-losing target system. However, experimental confirmation of the efficiency figure is yet to come.

During the second part of the Tuesday afternoon session, ejection systems for synchrocyclotrons were discussed. The papers read by the Chicago group and the Institute for Nuclear Problems (Phasotron) group showed that there is little variation in the methods used for ejection with this class of machines. Deflected beams vary from 2 to 6% of the circulating beam and, although the ejection efficiencies are much higher than used to be reached with simple scattering targets, they are still low. Another consistent feature of synchrocyclotrons is that many of the highest energy machines have a circulating beam of about 1μA mean. Since this can hardly be a fundamental constant, one would hope some day to learn that 10μA or more has been obtained.

The Wednesday morning session had as its subject linear accelerator injectors and injector techniques. All of the proton synchrotrons of 6 GeV energy and above use Linacs as preaccelerators and the fundamental design of these machines closely follows the original 30 MeV Linac built by Alvarez in Berkeley several years ago. The Brookhaven group described a research programme they had carried out to see if any alternative cavity structures would give a better performance than the Alvarez structure. Their conclusion was that for Linacs up to 50 MeV the Alvarez structure, using a cylindrical cavity and drift tubes, could not be sufficiently improved upon to justify designing a completely new structure. Certain modifications to the shape of the drift tubes however had shown marked improvements in power consumption. There is one change that has been made to the Alvarez system in both the 50 MeV Brookhaven injection Linac and the 50 MeV CERN injection Linac. In the Alvarez Linac, focusing of the beam was achieved by the use of grids placed in the drift tubes, and these grids produce considerable losses in beam intensity. The Harwell group in their design for a 600 MeV proton Linac, which they reported on during this session, had planned to use quadrupole magnets inside the drift tubes of the final stages of the Linac to give focusing while avoiding beam losses. Similarly, both the Brookhaven and CERN groups also plan to use quadrupole magnets as the focusing system and, due to the very low repetition rate of the synchrotrons (about 1 pulse per sec.), these quadrupoles can be pulsed, thus avoiding serious heating troubles inside the drift tubes. This change over from grid focusing to quadrupole focusing especially in the early stages of the Linac should give nearly a factor of 10 increase in beam intensity.

The CERN group reported on their studies into the problem of injecting the particles coming from the Linac into the synchrotron. The idea of matching the acceptance of the apparatus to the beam emittance was discussed in detail. Incorporated in the CERN design was a double bend magnet system to ensure that particles of different energy coming from the Linac were injected into the synchrotron along closed orbits appropriate to their energy. Such a system avoids extra betatron oscillations at injection and a consequent larger beam cross-section. The Saclay group also reported on an "Achromatic Inflector" and showed what improvements in beam capture at injection could result from its use.

Heavy ion linear accelerators designed as complete machines in themselves and not just as injectors for synchrotrons were also covered

during this session. The Harwell group described the design features of their 600 MeV proton accelerator which, for the moment at least, is only being built up to 50 MeV. A new idea for a heavy ion accelerator, essentially a "linear" accelerator bent round into an open circle, was put forward by the group from the Physical Technical Institute of the Ukranian Academy of Science. They proposed to overcome the beam losses at injection and ejection suffered by cyclic accelerators by using a curved linear accelerator and avoid the focusing problems of linear accelerators by bending the structure into an open circle by means of a magnetic field system similar to that used for strong focusing cyclic machines. Both radial and phase focusing can be achieved simultaneously in such a machine by choosing the parameters so that the stable phase is the same as in a synchrotron in which case the normal RF radial defocusing of the Linac becomes focusing. Effectively the machine works above the Transition Energy. The particles would be bent round the open circle (or any other suitable curve) by the magnetic field as in a cyclic machine and if the radius of curvature of the open circle is to be constant, there must be a spatial increase in the magnetic field intensity round the circle to compensate for the increase in energy of the particles. The magnetic field is however not time dependent as in a cyclic accelerator. It is probably too early yet to say whether such a machine would be markedly superior to a normal linear accelerator using quadrupole magnets as the focusing system. In either design, the length of the machine is still fixed by voltage breakdown considerations whether the accelerator is straight or bent into a circle. Whether or not it is worth while to consider linear accelerators for heavy particles in the GeV range is still not answered. No machines of this type for this energy range are being built at the moment and the only high energy machine that has been fully designed (for 600 MeV) has been stopped in favour of a higher energy proton synchrotron.

A paper was read by the group from the Institute of Chemical Physics (USSR Academy of Science) on high current linear accelerators. They described their work on Linacs in which beam currents of the order of a hundred milliamperes could be accelerated. Work on high current Linacs was also described by Prof. E. O. Lawrence at the Geneva conference in August, 1955. Machines of such high intensities, orders of magnitude higher than have been contemplated or achieved before with accelerators, will certainly be a welcome addition to the armoury of the accelerator technologists, whatever the reason for their development.

During the afternoon session on Wednesday, the non-linear theory of betatron oscillations in cyclic accelerating machines was considered. The papers presented by the CERN group, the Brookhaven group and the USSR Academy of Science group showed that there was agreement on the effects of non-linearities in the guiding field of cyclic accelerators on the stability of motion of the particles. However the theory so far is not complete and although the non-linear instability lines are well established in the "static" case, i.e. when the betatron frequency is not time dependent, theory has little to say about instabilities under "dynamic" conditions such as appertain to all machines which have synchrotron oscillations and frequency errors. However something is known about the dynamic behaviour of such non-linear systems from computing results and from model experiments. The phenomena of "lock-on" in dynamic non-linear systems for example was illustrated in the CERN paper. (Lock-on describes the motion of particles in a dynamic system which have been oscillating about the normal (linear) closed orbit and which, during the betatron frequency sweep through a resonance, choose a new closed orbit about which to oscillate.) The CERN group described a mechanical analogue which they had built to investigate the dynamic behaviour of non-linear systems and which so far had confirmed instabilities predicted by the theory in the static case. The Brookhaven group gave the results obtained with their electron analogue model which again confirmed the

static instability predictions. Methods of stabilizing non-linear systems were also discussed at length and illustrated by experimental results obtained from the models. It remains to be seen whether the models or the theoretical work can be extended to include the dynamic case in the near future.

The MURA group described the computing work they had carried out on the non-linear behaviour of particles in Fixed Field Alternating Gradient machines, particularly spiral ridge machines, in which the non-linearities are much stronger than in ordinary alternating gradient machines. Unfortunately it may not be possible to extend the theoretical work on non-linearities done so far to cover the case of strong non-linearities. Although the phase plots for the static case shown by the MURA group are certainly similar to those obtained by the other groups, it is perhaps too early to say whether spiral ridge machines are going to be more troubled by non-linearities than ordinary machines or not.

The problems discussed during the Thursday morning session concerned the magnets of accelerators. Accelerating machines work as well as their magnets permit and the papers presented by the CERN group, the Saclay group and the Institute of Nuclear Problems (USSR Academy of Science) group showed how seriously the design of magnets is being considered nowadays. The usual systems of correcting the errors inherent in magnets by auxiliary windings was discussed in detail and the Saclay group put forward a proposal for correcting for saturation effects in magnets by the use of crenellated pole pieces without auxiliary windings. A paper presented by the Australian group on the air cored magnet and power supply for their 10 GeV proton synchrotron showed how far they dared to extend technology in building an air cored magnet machine with a magnetic field higher than is possible using iron yokes magnets. The MURA group reported on experimental work on radial sector and spiral ridge magnets for their Fixed Field Alternating Gradient machines.

The Thursday afternoon session was on radio frequency accelerating problems. The first part of this session dealt with the problems of beam control which are becoming essential for the highest energy synchrotrons, especially the alternating gradient machines where there is a Transition Energy. A paper presented by the CERN group described the theoretical work that had been done to establish the optimum methods of achieving beam control, the information needed from the pick-up electrodes and the way in which this information should be applied to the accelerating cavities to keep the beam in the centre of the vacuum chamber. The Brookhaven group during the discussion described their experiences with beam control systems they have used on the electron analogue model of their 30 GeV synchrotron.

The second part of the session concerned the radio frequency systems of synchrocyclotrons. The Berkeley group and the CERN group described their designs for vibrating reed condensers as the active element for frequency modulating the radio frequency system. The group from the Institute of Nuclear Problems (USSR Academy of Science) gave a detailed account of the radio frequency system of their 680 MeV synchrocyclotron which uses a rotating condenser as the frequency modulator. Several papers were submitted on cavity design but only one was read at the session.

The problems of designing high energy electron synchrotrons were discussed during the Friday morning session. The MIT-Harvard group presented a paper on their proposed 6 GeV electron machine which has just emerged from the general design stage. The radio frequency system for this machine presents a formidable problem due to the high energy loss of the electrons due to radiation. In a machine of 30 m radius, this energy loss is as high as 4.4 MeV per revolution at an electron energy of 6 GeV and 10.7 MeV per revolution at an electron energy of 7.5 GeV, the energy loss increasing as the fourth power of the particle energy. Sixteen cavities distributed round the machine, each with a peak radio

frequency voltage of 1 MeV, will compensate for this loss and accelerate the particles. The peak RF power required is 25 KW per cavity at 6 GeV energy. Since the machine is designed to operate at 30 pulses per sec., to obtain the desired high intensity, the mean power required from the radio frequency amplifiers is also high, being about 5 KW per cavity at 6 GeV energy. The high intensity from this machine, estimated to be hundreds of times higher than an equivalent energy proton machine, is necessary to offset the factor of one hundred between electromagnetic and nuclear induced reactions. Such a machine should be useful for the study of proton anti-proton pair production (threshold 3.8 GeV for X-rays), meson and hyperon production and pair production of "shower particles", photo production of pions, muons and nucleons, and electron structure studies.

The serious problem of radiation and relativistic motion in electron synchrotrons was dealt with extensively by the USSR Academy of Science group in their paper and during the discussion that followed. There now seems to be more agreement about the theoretical predictions on this subject.

The afternoon session on Friday was different from the other sessions in that the subject under discussion was as much a problem of organization as of technology. The papers presented dealt with the use of accelerators after construction, or more explicitly the management and utilization of machines. When one has spent many years and many millions of units of the local currency in building an accelerator, it is of paramount importance that full use is made of the operating time of the machine in carrying out nuclear physics experiments. Machines have a relatively short front-line life and must be exploited accordingly. The papers of the Brookhaven group on the Cosmotron, the Berkeley group on the Bevatron and the Institute of Nuclear Problems (USSR Academy of Science) group on the 680 MeV synchrocyclotron demonstrated the intricate organization of the experimental programme necessary for full exploitation. Nuclear physicists not acquainted with machine physics and more used to a University research time scale must have been horrified at the rigors and discipline to which high energy nuclear physicists are submitted these days.

The last session of the week on Saturday morning covered general topics not dealt with during the week. The paper by the Princeton group on their 3 GeV high intensity proton synchrotron has been mentioned earlier. The Stanford group presented a paper on high energy electron Linacs in which they outlined a design for a Linac of energy greater than 10 GeV, in the energy range where the radiation losses make a cyclic electron machine impracticable. The number of klystron amplifiers needed for powering such a large machine and the life of a klystron present formidable supply problems and high maintenance costs.

The Physical Institute group and the Institute of Nuclear Problems (USSR Academy of Science) group ended the session with two papers, one on a cyclotron with sectioned magnets similar to the clover-leaf cyclotron described by the Berkeley group last year and one on their experiences in running the model of their 10 GeV proton synchrotron.

The conference ended with a visit to the CERN Laboratories in Geneva and to the CERN site at Meyrin where a 600 MeV synchrocyclotron and the 25 GeV proton synchrotron are in course of construction.

If any conclusion can be drawn from the conference, it must be that accelerating machine projects are in no way dying from lack of nourishment. More money seems to be available to build machines nowadays than ever before, more physicists and engineers seem to be working on accelerator designs than one remembers in the past and there is no lack of ideas for new machines and new projects. There seems every reason to expect that the next conference on this subject, to be held in Geneva in 1958, will be just as exciting.

NUCLEAR INSTRUMENTS 1 (1957) 10–16; NORTH-HOLLAND PUBLISHING CO. – AMSTERDAM

THE CERN SYMPOSIUM 1956 (II)

G. F. VON DARDEL

CERN, Geneva

Received 14 September 1956

The second week of the symposium was devoted to the measurement instruments and apparatus used with high energy accelerators and to recent results in some fields of high energy physics. In this review article will be treated the sessions on the various types of nuclear instruments, such as bubble and cloud chambers and counters, and the scientific sessions on antiproton physics and nucleon-scattering.

1. Bubble Chambers

The first session concerned bubble chambers and started with an invited lecture by D. A. Glaser, the first to construct a working bubble chamber. Since the first tracks were obtained in a small bubble chamber four years ago tracks have been obtained in a wide assortment of liquids. The dimensions of the bubble chamber has been increased from 1 inch in diameter to the 72 inch long hydrogen chamber under construction by Alvarez. While the bubble chamber has thus the advantage of great flexibility, it cannot like the cloud chamber be used with countercontrolled expansions, due to the short life time of the "latent image". This feature limits its usefulness for cosmic ray research and the main application will be with accelerators.

In another paper presented at the symposium Bertanza and coworkers from the University of Pisa have however indicated a possible method to overcome this disadvantage by rapidly creating the supersaturated condition necessary for bubble formation after the ionising event by the application of an intense pulse of microwave power from a magnetron instead of by expansion. Boiling of the liquid was indeed observed only when the microwave power was triggered by a counter telescope, but the bubbles formed did not form tracks under the conditions of this preliminary study.

A bubble chamber can be operated to record events at every pulse of a large accelerator and a large number of photographs will be recorded very rapidly. The main time will be consumed in the analysis of the photographs. It is therefore essential to automatize the analysis of the recorded events as much as possible. Glaser sketched such a method which involved measuring the coordinates of successive points along the tracks in the two stereoscopic photographs and automatically recording these coordinates on punched cards. These punched cards would be fed to an electronic computer which calculates the true three-dimensional coordinates of the measured points, applying the necessary corrections for the refraction in the liquid and glass windows and other sources of distortion. From these coordinates the computer proceeds to calculate the parameters of interest such as track lengths, angles between tracks, magnetic curvatures, multiple scattering etc., and then tries out the momentum-energy balance for various possible particle assignments.

Glaser also reported on his most recent work, on liquid xenon bubble chambers. Pure liquid xenon failed to give tracks in a small bubble chamber. It is probable that this is due to the fact that pure xenon is a good scintillator so that part of the energy is given off as light and is lost to the bubble forming process. Quenching the scintillations by adding 2 % by weight of ethylene gave a workable bubble chamber liquid.

It is now intended to make a large xenon chamber, in spite of the high cost of liquid xenon. In such a chamber not only charged particles but also gamma rays and neutrons will be detected by the electron pairs and exchange protons produced in the liquid. The complete decay schemes of an unstable particle into charged and uncharged particles can thus be studied.

Two reports were presented on the construction of liquid hydrogen bubble chambers. Alvarez reported on the work in Berkeley where, after preliminary work on a 2.5 inch and a 4 inch chamber, a 10 inch diameter chamber is now in operation in a magnetic field of 8000 gauss. Expansion is done on the gaseous phase and rapid recompression reduces dead time and hydrogen consumption. The chamber has been used in a study of scattering of 700 MeV pions and in preliminary runs near the Bevatron several examples of associated production of strange particles have been found. Distortion of the tracks due to turbulence is found to be negligible, and the spurious curvature of the tracks without field is 30 to 50 meters so that precise momentum measurements, limited essentially only by multiple Coulomb scattering, are possible. Under design is a very big hydrogen bubble chamber 72 by 20 by 15 inches to be operated in a magnetic field of 15 000 gauss.

R. H. Hildebrand, Chicago, reported on a small, $1'' \times 1'' \times 4''$ liquid hydrogen bubble chamber, of the "clean" type. Photographs are taken at right angles 15 milliseconds after the passage of a particle. The "clean" feature allows the chamber to remain sensitive during $^1/_4$ sec after each expansion. This bubble chamber has been used in a study of the scattering of low energy pions against protons. Pions and electrons could be distinguished on the basis of bubble density. The scanning time was about 4 hours per 1000 pictures under conditions where about 15 cm track was recorded per photo.

A bubble chamber containing liquid helium has been studied by E. M. Harth *et al.* at Duke University. There is considerable interest in such a helium bubble chamber since it is ideally suited for testing charge independence and the isotopic spin assignments of strange particles by measuring the production and absorption cross sections in helium. A 10 liter helium bubble chamber is now under construction.

The dependence of the bubble density in a bubble chamber on the operating conditions of the chamber and on the ionization produced by the particle is of great imporance since it may be used for the determination of the velocity of the particle. Several papers on this problem were given. D. Glaser reported that the bubble density in a propane chamber can be written as the sum of a temperature independent term proportional to β^{-2} and a temperature dependent constant. If highly relativistic particle tracks are present in the photo their bubble density can be used to eliminate the temperature dependent term, making a rigid temperature control unneccessary. In addition the bubble density as a function of temperature exhibits a plateau, a fact which was also found by the workers of Padova University. A Russian group reported, in some disagreement with Glaser's findings, that the bubble density in propane is proportional to β^{-2} except in the highly relativistic region where evidence is found for an increase in bubble density with velocity, probably due to the relativistic increase in ionisation above the minimum.

2. Overcrompession Chambers and other Track Chambers

While the more recently developed bubble chamber has many advantages the role of the conventional Wilson chambers is not yet finished and several papers treated the suitability of this instrument for use with accelerators. In a discussion of the relative merits of diffusion and expansion cloud chambers and of bubble chambers for use with accelerators C. C. Butler and J. L. Redding point out that in the high energy region a chamber of large dimensions is necessary for accurate magnetic curvature measurements and the Wilson chamber will then constitute the cheapest solution. The low density of gaschambers can be overcome in part by using high pressures and the recovery time can

be reduced by using overcompression. Butler and Redding give design featurs of a 20 atmosphere hydrogen-filled expansion cloud chamber.

N. C. Barford gave a review of the work done so far on the use of overcompression and fast recompression to reduce the deadtime of an expansion cloud chamber. Overcompression probably gives a shorter cycle than fast recompression and certainly produces better quality photographs. Cycles of about ten seconds can be achieved for shallow chambers, making them suitable for work with many particle accelerators, and about one minute for large chambers for cosmic ray work. With a sensitive time of 100 msec the duty cycle of the cloud chamber can be made as high as 1/300, so that random experiments requiring a few hours sampling time become feasible.

Prof. M. Conversi reported studies of a new type of track chamber, the so called hodoscope chamber, which consists of a large number of thin glass tubes filled with a suitable counter gas. If a high electrostatic field is applied to these tubes within a few microseconds after the passage of a charged particle by applying a high voltage pulse to a series of metal plates, a visible discharge is produced in those tubes traversed by the particle. A photograph taken from the end side of the tubes will show a rough picture of the path of the particle.

Prof. E. Amaldi reported on the construction of an electronic scanner for nuclear emulsions intended to count the number of parallel track incident on the emulsion. The direction of the track is defined by a series of three slits with photomultipliers behind them. As the film is moved past the slits a threefold coincidence is obtained when a track of the correct direction passes the slits. The emulsion can be scanned at a rate of about 1 cm/sec and 10^3 to 10^4 tracks per second can be recorded. Such an apparatus should prove extremely helpful for scanning emulsions exposed to accelerators.

3. Čerenkov Counters and other Fast Counter Techniques

Recent years have seen a considerable growing interest in the Čerenkov counter and it has been used in several experiments. Several papers on this subject was presented at the symposium and additional information were given during the discussions after the papers.

J. Marshall, Chicago, reviewed in an invited paper the fundamental properties of the Čerenkov light. The emission of the light in a cone determined by the velocity of the particle makes it possible to construct Čerenkov counters sensitive only to particles within a limited velocity region. Marshal discussed in particular the type of counter where the Čerenkov light from particles having the correct velocity is focused onto a hole in a diaphragm which rejects the light from particles having the wrong velocity. From angular momentum considerations it follows that the Čerenkov light cannot be focussed to a spot on the optical axis much smaller than the cross section of the beam, but it is possible to get a sharp ring focus. The sharpness of the Čerenkov cone and the obtainable velocity resolution is limited by multiple Coulomb scattering and the change in velocity of the particles along the track due to slowing down, and by optical dispersion of the Čerenkov substance. The relative importance of these three factors have been studied for lucite, quartz glass, lithium fluoride and water for protons between 422 and 563 MeV. For lucite the limit is essentially set by the optical dispersion while for the other substances the three factors are equally important. The effect of optical dispersion can be decreased by the use of filters which limit the range of wave lengths at the expense of intensity. The effect of the slowing down of the particles can be counteracted if the radiator is built up of elements tapered in such a way as to compensate for the change in Čerenkov angle. A practical example of a velocity selecting Čerenkov counter was described in a separate paper presented by O. Chamberlain, Berkeley. In order to eliminate spurious counts due to the thermal noise of the photomultipliers, the

optical system was split into 3 parts and the output of each detected with a photomultiplier. Requiring a coincidence between at least two of these and with scintillation counters before and after the Čerenkov counter gave a sufficiently low background while particles in the correct range were detected with 97 % efficiency. For protons with a velocity 0.03 c higher or lower than the center value, the efficiency drops to a background value of 3 %, probably due to fast particles generated in nuclear interactions with the radiator. Chamberlain points out that this type of counter is not useful for lighter particles than protons since the energy loss would be excessive in the velocity region of interest. Chamberlain also gave information on a different type of velocity selective Čerenkov counter used by Fitch. In this counter the lower velocity limit is set by the Čerenkov threshold while the upper limit is given by the fact that for large Čerenkov angles the light will be totally reflected at the far side of the radiator and will not reach the photomultiplier. The disadvantage of this type is that the selected velocity interval is given essentially by the optical properties of the Čerenkov substance and cannot readily be changed.

A somewhat different type of velocity selective Čerenkov counter used with the Birmingham accelerator was described by J. V. Jelly. This counter is of the type originally suggested by Getting and consists of a perspex cone with an angle chosen in such a way that the Čerenkov light from particles of the correct velocity traversing the cone along the axis is reflected parallel to the axis. The light is then focussed by a lens onto a hole in a diaphragm in front of a photomultiplier. The particle velocity for which the counter is sensitive can be modified by interposing conical lenses after the perspex cone. The counter is characterized by a very high efficiency for the collected light. The collected light against proton energy shows a peak with a width at half-maximum of $\pm$ 12 %. The light intensity also depends sharply on the angular alignment of the beam with the optical axis.

I. Chuvilo, Moscow, considered a velocity selecting Čerenkov counter of a different type to be used in the region of high energies where a very high resolution is necessary in order to distinguish between particles with different mass but the same momentum. The main principle of these ideas is to use interference filters as commonly used in optics to select light within a very narrow range of Čerenkov angles. It was hoped that with such a counter it would be possible to distinguish pions and muons up to 10 GeV.

Apart from the velocity selecting Čerenkov counter the main interest was focussed on the total absorption Čerenkov counter first suggested by Hofstadter. The energy of a high energy gamma-ray or electron is entirely dissipated as an electron shower inside the counter, which gives rise to a pulse of Čerenkov light, proportional to the energy of the gamma ray. J. M. Cassels described a lead glass counter which had been used in Liverpool in a study of the Panofsky ratio. The pulse height spectrum obtained with the gamma rays from the absorption of π^- in hydrogen was measured and analysed in terms of the capture gamma ray and the decay gamma rays of the π^0 G. Bernardini, Illinois, described measurements with a lead glass counter of similar construction, having a length of 35 cm (14 radiation lengths) and a diameter of 30 cm. The expected performance of this counter had been calculated by the Monte Carlo method and was compared with experimental curves obtained with monoenergetic electrons. The efficiency of the counter for electrons and gamma rays higher than 100 MeV is very close to 100 %. The width of the peaks in the pulse height distribution was however twice as wide as expected from the Monte Carlo calculations. This fact is probably due to absorption of Čerenkov light in the lead glass, so that the number of photoelectrons emitted by the photocathode is smaller than expected and the statistical fluctuations larger. It is hoped that lead glass will become available having higher transmission within the region of the photocathode spectral response curve. At present only about 10 % of the cathode spectral response

curve falls within the region not strongly absorbed by the lead glass.

Prof. R. Hofstadter, Stanford, reported that attempts are made by the Harshaw Chemical Co. to grow large crystals of PbF_2 which has a specific density of 8.0 grams/cm³ and good transparency. Fidecaro, Liverpool, reported on an investigation of saturated leadperchlorate solution, having a density of 2.77 g/cm³. The transparency for these solutions per radiation length extends further into the ultraviolet than for lead glass but the necessary dimensions are larger. Osborne summarized investigations at MIT of a sandwich counter of 50 scintillating layers interlaced with lead foils and of a large scintillation tank, both to be used as total absorptions counters. Another method would be to mix leadglass chips with a scintillating liquid.

Čerenkov counters of low refractive index for the rejection of non relativistic particles were also discussed. R. Hofstadter reported that he had used a counter of liquid $C_8F_{16}O$ ($n = 1.276$) to reject a background of pions which showed up when a lucite ($n = 1.5$) Čerenkov counter was used. No convenient materials with lower refraction index exist however apart from the liquid gases, until one comes in the range of the compressed gases. Stable aerosols, if sufficiently transparent, may offer a solution in this range.

A very interesting paper on the precise determination of ionization using multilayer proportional counters by A. I. Alikhanov and his group was presented by V. A. Lubinov. In evaluating the pulse heights obtained from a multilayer proportional counter the ordinary method of taking the arithmetic mean is very inefficient due to the long tail on the Landau distribution. Several more efficient methods of evaluating the results are suggested, such as fitting the resulting pulse-height histogram to a Landau curve, by taking the arithmetic mean of the n smallest pulses, n being a suitable fraction of the number of layers, and by forming the geometric instead of the arithmetric mean of the pulse heights. The two last methods are almost as efficient as the first and can be performed automatically by electronic circuits. For a large number of layers the last method is most economic in valves. Experiments with a five-layer proportional counter have shown that pions, K-mesons and protons can readily be distinguished by the momentum ionization-method up to a momentum of 720 MeV/c. Above this value the pion and K-meson peak in the mass distribution merge but up to a momentum of about 1000 MeV/c it is still possible to obtain a measure for the proportion of these particles in the peak from the position of the center of gravity of the peak. A 50 layer proportional counter has been built and successfully tested. With this counter it should be possible to achieve a precision of the ionisation determination of 2 % and to separate pions and K-mesons of the same momentum at energies as high as 7 GeV by means of the relativistic increase in ionisation above the ionisation minimum.

Chamberlain, Berkeley, gave an account of the advances in the millimicrosecond counting techniques made necessary by the introduction of the Čerenkov and other fast counters. Faster photomultipliers than used at present will be needed, giving sufficient output to operate directly coincidence and other circuits, since otherwise the speed will be limited by the rise time of the amplifiers. A step on this road is the RCA type 6810 photomultiplier, which at present has a rise time of 6 mμsec, a figure which by suitable changes can be improved by a factor of 5. Much hope is also attached to the work of Sternglass on a transmission type photomultiplier where the electrons traverse thin gold foils and produce secondary electrons in a KCl layer on the far side. This work is however still in a very preliminary state. One has also to consider transmission of the signals over long distances without deterioration of the rise time. Thick, rigid, cables insulated with styrofoam are very good from this point of view.

With the fast counting techniques now available time-of-flight techniques become feasible in the 100 MeV region. Dr. G. H. Stafford described work to pulse the Harwell cyclotron by pulsing a deflection plate so that the "sausages" of ions accelerated in the machine are

deflected vertically onto a target. In this way bursts of neutrons can be produced with a length of 20 mμsec. The deflection pulse is produced by a system of thyratrons properly phased to the R. F. voltage of the machine which cause a spark gap to break down, discharging a capacity, charged to 100 kV into the deflector plate. For the analysis of the time-of-flight delays a time to amplitude converter will be used in conjunction with a kicksorter.

4. Antiproton Physics

A short session was devoted to the recent experiments in Berkeley in collaboration with the University of Rome and other laboratories, which lead up to the discovery of the antiproton and a study of its properties. The design of the antiproton channel was described by O. Chamberlain. The channel consists of two momentum defining deflection magnets with associated focussing quadrupole lenses. The incoming and outgoing beam of the second magnet are defined by two scintillation counter. Since the distance between these counters is 12 meters it is possible to discriminate between mesons and antiprotons of the same momentum on the basis of the time-of-flight between the counters which is 40 and 51 mμsec respectively. An ordinary Čerenkov counter with low index of refraction so that it does not respond to antiprotons of the proper momentum is used in anticoincidence to reject mesons and the velocity selecting Čerenkov described above is used to check again that the velocity is within the correct range. This channel was first used to verify the existence of negative particles of proton mass and has then been used as a source of antiprotons for various experiments. The total cross section has been measured and analysed in terms of annihilation and scattering, using an array of a water Čerenkov counter and scintillation counters. Terminal phenomena of the antiprotons have been studied by sending the beam into a big lead glass counter, which essentially detects the decay gamma rays from neutral pions generated in the annihilation process. Other terminal studies have been made with stacks of nuclear emulsions in another magnetic channel. Antiproton annihilation events in nuclear emulsions were discussed by Prof. Amaldi, Rome.

5. Nucleon-Nucleon Scattering

This session was mainly devoted to the work on nucleon-nucleon scattering carried out with the 660 MeV synchrocyclotron in Moscow. In this review only some of the instrumental features of the work reported will be discussed while the reader is referred to the proceedings of the symposium for a discussion of the scientific results.

A paper by Dzelepow *et al.* treated the elastic scattering of 580 MeV neutrons by nucleons. The scattered neutrons were detected by a conventional recoil counter telescope using three "tolan" scintillators with a tungsten absorber in order to register only the high energy end of the incident neutron spectrum after elastic collisions. In this work as well as in other Russian investigations a resolving time of the coincidence circuit of 5.10^{-8} sec was used. Another paper by Mescheryakov *et al.* presented results on the scattering of 460 and 660 MeV protons by protons and deuterons. These measurements were greatly facilitated by the presence of the extracted proton beam of the Moscow machine. In the p-p-scattering experiments the scattered particle only was recorded by counter telescope, while in the p-d-scattering two telescopes recorded both the scattered and the recoiling particle. The angular correlation made it possible to distinguish between elastic p-d-collisions and collisions with a nucleon in the deuteron. The incoming beam was monitored by a helium or argon-filled ionisation chamber. Mescheryakov also presented a paper by Bogomolov *et al.* on small angle p-p-scattering at 660 MeV. In these measurements a water Čerenkov counter was included in anticoincidence in the counter telescope in conjunction with tungsten absorbers which reduced the velocity of the scattered protons below the Čerenkov threshold. Pions trigger the Čerenkov counter and are thus rejected, while deuterons and slow protons will be absorbed by the absorbers.

A second paper by Mescheryakov *et al.* reports on polarisation experiments with two proton beams from the Moscow cyclotron, which emerge after being scattered through 9° and 18° by an internal beryllium target. The smaller angle scattering will be primarily diffraction scattering as verified by the energy-distribution, while the other beam will contain an appreciable amount of quasi-elastically scattered protons. Studies of the polarisation of the two beams by asymmetry measurements indicate a polarisation of about 60 % for the small angle scattered beam and 33 % for protons scattered at 18°.

The last lecture of this session was a paper by Holt *et al.* on p-p-scattering at 383 MeV performed with the external beam of the Liverpool cyclotron. The external beam is bent and focussed at a distance of 12 meters from the cyclotron where the targets are placed. The beam cross section here is 10 by 15 mm and the flux 10^7 protons per second. Differential cross section measurements are made with an accuracy of about 1 %.

In the discussion after the session Smorodinski Moscow, pointed out that from the theoreticians point of view five experiments are necessary to define all the parameters of nucleon-nucleon scattering, namely ordinary scattering experiments, polarisation experiments, the triple scattering experiments of the Wolfenstein type, and experiments to give the correlation between the planes of polarisation of the scattered and recoiling nucleon. Experimentalists will have a hard time to fulfil these requirements.

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THE CERN SYMPOSIUM 1956 (III)

ARNE LUNDBY

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The last few days of the Symposium were mainly devoted to the branch of high-energy physics which deals with π-mesons (pions). In a few papers, however, work was also reported on the scattering of high-energy electrons and photons on nucleons.

The interaction of pions with nucleons and nuclei is understood to the extent that symmetry properties like charge, angular momentum and parity give rise to relationships between reaction cross-sections which agree with experiments. Both production by photons and nucleons and scattering of pions on nucleons give strong evidence for the existence of (at least) one excited state of the pion-nucleon system. This fact is manifested in resonance phenomena in the mentioned processes and has been explained qualitatively by different theories. As to the details of the interaction of pions with nucleons no satisfactory theory exists. This is partly due to a lack of experimental information to guide the theorists. The reports at the Symposium revealed an increasing amount of experimental material from different parts of the world on the pion-nucleon interaction which fit together very well. The statistical accuracy in the cross-section data is now in many cases so small (of the order of 1 %) that systematic errors are the main source of uncertainty. In order to avoid systematic errors more careful measurements are being performed, sometimes with improved or even new experimental techniques.

1. Pion-Nucleon Scattering

L. C. L. Yuan (Brookhaven) gave a survey of the investigations of pion-nucleon scattering done in U.S.A. Total cross-sections have been measured with the Brookhaven Cosmotron up to 4 GeV kinetic energy of the pions. Besides the resonance somewhat below 200 MeV the cross-sections for both positive and negative pion-scattering on protons have maxima in the GeV region which might be attributed to additional resonances.

The most complete information on pion-nucleon scattering still comes from work with synchrocyclotrons. At the moment the synchrocyclotron of highest energy (680 MeV protons) is at the Institute for Nuclear Problems near Moscow. This accelerator is capable of producing pions with kinetic energy above 400 MeV. At the moment the proton beam current in the machine is only of the order of 0.1 microamperes (ten times larger current has been obtained elsewhere), and the intensity of pions at the maximum energy is therefore too small for doing accurate experiments.

The Russian physicists have measured the angular distribution of scattered pions on protons with energies of initial pions up to 310 MeV. Until a year or so ago the pions were produced on a target inside the machine, and the pions were bent out and to some extent focussed in the fringing field of the magnet. Much more intense beams of higher energy pions resulted when efficient procedures for extracting the protons from the machine were developed (see summary by Adams). The Russians use such an extraction procedure and can therefore work with positive pions up to 310 MeV.

The experimental techniques used by the Russians (as reported by A. I. Mukhin), the Americans (experiments with pions up to 220 MeV at Pittsburgh reported by J. Ashkin) and

the English are quite similar. Whenever possible (large enough intensity of particles with kinetic energies above some tens of MeV) scintillation counters are used to detect the primary and scattered pions. A typical scattering arrangement is shown in the figure.

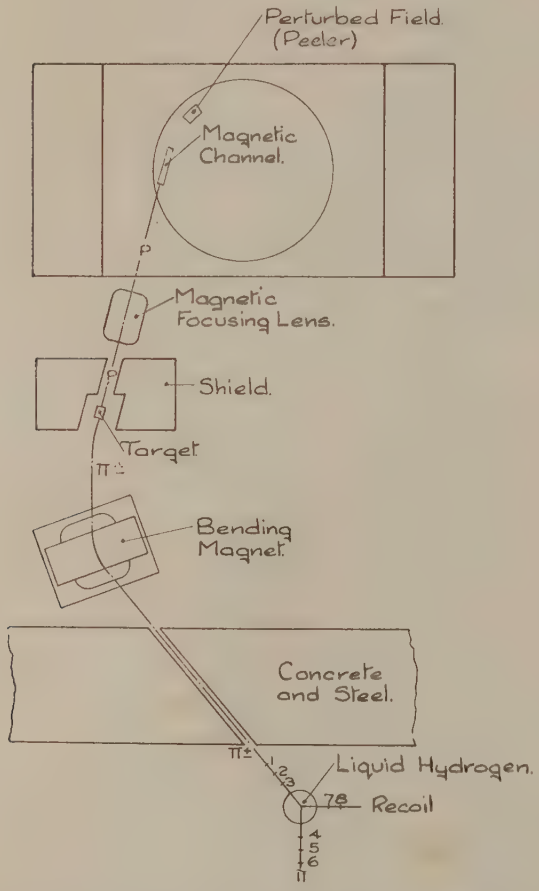

Fig. 1. Schematic diagram of pion-proton scattering arrangement with external beam from synchro-cyclotron

When the protons reach the periphery of the synchrocyclotron they enter a region in which the magnetic field has been perturbed. By proper adjustments of the perturbing field the protons are forced into radial oscillations which bring them out to a magnetic channel which in turn guide the protons out of the machine. There they are focussed to the target (plastic, carbon, beryllium, copper etc.) in which the pions are produced. To select pions of desired charge and momentum a bending magnet is used which directs the pions to the experimental room. Here the scatterer, a few litres of liquid hydrogen in a styrofoam container, is located. Together with positive pions come protons, muons and positrons of the same momentum. The protons can be eliminated from the beam with an absorber. The discrimination against muons and electrons is more difficult and is done either with a Čerenkov counter (1 in the figure), or by measuring the time of flight between two of the scintillation counters (for example 2 and 3). These counters usually consist of an organic liquid (e.g. p-terphenyl in phenylcyclohexane) or plastic scintillator coupled to a photomultiplier.

The scattered pions and recoil particles are registered with scintillation counters 4, 5, 6 and 7, 8 respectively. By swinging the arms of the last counter telescopes the angular distribution of scattered pions are measured. While waiting for statistics to build up great stability is required in the fast detection schemes. The results are fed into electronic calculating machines which fit the data together and produce quantities which can be compared with theory.

Low energy scattering processes (in the 10 MeV region) can most conveniently be studied with track chambers. In this case the hydrogen scattering target in the figure is replaced in favor of the track chamber. D. Nagle (Chicago) and W. H. Evans (Liverpool) reported at the Symposium on pion-nucleon scattering experiments with hydrogen bubble-chamber and diffusion chamber respectively. These techniques have been described previously (see summary by von Dardel).

Finally analyses of tracks of scattered particles in photographic plates were described by A. I. Mukhin (Moscow) and G. Puppi (Bologna).

When negative pions are stopped and captured by hydrogen, either a neutral pion or a gamma ray is emitted[1]). The ratio of these two events (determined first by Panofsky) is measured by

[1]) The reactions involved are

$$\pi^- + p \rightarrow \pi^0 + n \rightarrow 2\gamma + n$$
$$\pi^- + p \rightarrow \gamma + n$$

quantitatively determining the energy spectrum of the gamma rays. The neutral pions decay into two gamma rays with energies varying from about 56 MeV to 84 MeV while the simple radiative capture reactions result in gamma rays of about 129 MeV.

Measurements of the Panofsky ratio are in progress at Liverpool. A. W. Merrison reported on measurements with a magnetic pair spectrometer. In this case the gamma rays are converted into electron-positron pairs and the energy of these pairs determined by deflection in opposite directions in a magnetic field. So far the results give for the ratio 1.38 ± 0.20.

J. M. Cassels, on the other hand, measures the gamma ray spectrum with a total absorption Čerenkov spectrometer. The gamma rays produce showers in lead-glass, and the total Čerenkov light emitted by the electrons and positrons in the showers is collected by a photomultiplier. The width at half-maximum of the pulse-height curve of total absorption Čerenkov counters is at the moment 25–30 % in the best cases. Cassels deduced from his measurements a value 1.46 ± 0.20 for the Panofsky ratio.

Investigations of the interaction of pions with complex nuclei were also described. L. M. Lederman (Columbia) use a diffusion cloud chamber to look at reactions of 30–180 MeV positive pions on deuterium. A. E. Ignatenko (Moscow) described extensive measurements of the interaction of negative pions of 140–400 MeV with a number of complex nuclei. The techniques used comprised scintillation counter telescopes in transmission measurements, expansion and diffusion chambers and photographic plates to look at tracks of individual events.

2. Photo-Meson Production and Scattering of Photons and Electrons by Protons

The creation of mesons in collisions of gamma rays with nucleons depends on the interaction of nucleons with the electromagnetic field besides the nucleon-meson interaction. In a survey of such processes G. Bernardini (Illinois) showed that experiments so far can generally be interpreted by combining our knowledge of nucleon photon and nucleon-meson interactions.

The experimental techniques are in this case adapted to the high gamma ray background in the vicinity of electron synchrotrons. Photographic pellicles surrounding a liquid hydrogen target in the Bremsstrahlung beam of the Illinois synchrotron have been scanned for pion-muon decays by M. Beneventano *et al.* (Rome). The M.I.T. group, as reported by L. S. Osborne, is using a combination of scintillation and Čerenkov counters to detect the two gamma rays emitted in the decay of neutral pions. Charged pions produced at small angles to the Bremsstrahlung beam are registered by the muon-electron decay with scintillation counters in delayed coincidence. The counters are switched on when the primary beam pulse from the synchrotron (one microsec long) is over.

M. I. Adamovitch (Moscow) reported measurements on the production of negative pions from neutrons in deuterium with gamma rays from the 250 MeV electron synchrotron at the Lebedev Physical Institute in Moscow. The Bremsstrahlung beam was allowed to traverse nuclear photoplates loaded with heavy-water. The plates were afterwards scanned for stars consisting of two protons and a meson. The results show that the process is associated with a spin flip of the nucleon near threshold for the reaction.

A. C. Belousov of the same Institute described measurements of neutral and negative pion production on complex nuclei with a scintillation counter telescope and photographic plates respectively. The production processes seem mainly to take place at the surface of the nuclei.

The Compton scattering of photons on protons is difficult to measure when the energy of the photons is above the threshold for neutral pion production. This is of course to a great extentdue to background from pion decay gamma rays. G. Bernardini described experiments in progress at Illinois in which the scattered gamma rays are recorded with a total absorbtion Čerenkov detector (lead glass) in coincidence with a scintillation counter which detect the recoil protons after they have been deflected in a magnetic field.

The distribution of charge and magnetic moment of the proton is being investigated by R. Hofstadter and coworkers with the Stanford electron linear accelerator. Electrons with kinetic energy up to 550 MeV are scattered against hydrogen, and the angular distribution measured. The scattered electrons are selected in a 180° double-focusing spectrograph and registered with a well-shielded lucite Čerenkov counter. Large deviations from a point proton are found, indicating rams radius for charge and moment distributions in the proton of 0.8×10^{-13} cm.

3. Pion Production by Nucleons

An extensive material on the production of pions with protons on nucleons and complex nuclei was disclosed at the Symposium.

A. W. Merrison (Liverpool) and W. O. Lock (Birmingham) gave surveys of pion productions in proton-proton reactions at low energy and at 400–1000 MeV respectively. Experiments up to the highest energies indicate a strong production through the previously mentioned isobar state of the pion-nucleon system.

W. H. Evans (Liverpool) and J. Walker (Birmingham) described work with cloudchambers, while W. O. Lock and H. Muirhead (Glasgow) reported measurements with photographic plates in the proton beam of the Birmingham synchrotron. These experiments are still in progress.

Very extensive measurements of the energy spectra of charged pions were described by M. G. Mescheryakov and his coworkers (Moscow). The 660 MeV external proton beam from the Russian synchrocyclotron was allowed to strike a target (see previous figure) and the emerging particles (pions, protons and deuterons) were analyzed with a magnetic spectrometer. Scintillation counters, even in the magnetic field, secured that the particles recorded had not been scattered by the pole pieces of the analyzing magnet.

Investigations on production of neutral pions have also been performed in the same laboratory (Yu. D. Prokoshkin, Y. D. Bayukov *et al.*). Both internal and external targets were used. The decay gamma rays of neutral pions were detected with a telescope of scintillation and Čerenkov counters.

In proton-proton collisions at energies above 1 GeV more than one pion is frequently produced. M. M. Block (Duke) gave results of measurements with a hydrogen-filled diffusion cloud-chamber in the proton beam from the Brookhaven Cosmotron. At 2.75 GeV the percentages of single, double and triple pion production were estimated to be 35 %, 48 % and 16 %.

4. Mesic Atoms

When a negative pion or muon is stopped and captured by a nucleus it will usually first suffer radiative transitions in the Coulomb field of the nucleus with the emission of X-rays and Auger electrons. A study of these transitions give information on the pion-nucleon interaction and the electric field near nuclei. A. Roberts (Rochester) discussed these questions and presented some experimental results.

Since the X-rays in question mostly have energies below 100 keV, scintillation spectrometers can only give poor indication of energies. D. West (Harwell) therefore uses proportional counters, while M. Stearns (Pittsburgh) uses critical absorbers to determine the energies of the X-rays.

The proportional counter used by West is filled with xenon at 3 atm. The standard deviation of the pulse-height peak is 6 % at 10 keV and 2 % at 80 keV, which is five times better than with NaI(Tl)-crystals. The efficiency of the proportional counter (5 % at 60 keV) is, on the other hand, nearly 20 times smaller than for NaI(Tl) of reasonable dimensions.

The experimental apparatus used by Stearns consists of a NaI(Tl) scintillation spectrometer with critical absorbers between pion capture medium and scintillation crystal.

Negative muons have a weak interaction with nuclei and a relatively long lifetime. When captured in the Coulomb field of a nucleus the muon either decays into electron and neutrinos or it is captured by the nucleus. L. M. Lederman (Columbia) described measurements of the lifetimes of muons in different nuclear Coulomb fields by counting primary muons and decay electrons with scintillation counters.

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REGENERATIVE ACTION IN HIGH ENERGY ACCELERATORS†

STANLEY COHEN †† and ALBERT V. CREWE

The Enrico Fermi Institute for Nuclear Studies The University of Chicago

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It is shown that the regenerative method for the extraction of particles from an accelerator can be extended to include machines other than cyclotrons. This is accomplished by the use of modes of radial oscillations in which the regenerative action does not occur on every revolution of the particle about the machine. In particular, that mode of oscillation which allows regenerative action on every other turn is analyzed and shown to permit extraction from circular machines whose values of n

$$\left(n = -\frac{R}{H}\frac{\mathrm{d}H}{\mathrm{d}r}\right)$$

lie near 0.75. An extension of the analysis to machines with straight sections and strong focussing machines is included

1. Introduction

Many methods have been used to extract the circulating beam from high energy synchrocyclotrons with varying degrees of success. These include, among others, the pulsed electrostatic system[1]), scattering from a thin, high Z target into a magnetic channel[2]), and merely allowing the particles to "spill out" around the machine[3]), the most successful method, however, has been the regenerative method, first proposed by Tuck. Following the initial calculations of Tuck and Teng[4]), this system was investigated by LeCouteur[5]), using a matrix technique and shown to be capable of removing a considerable fraction of the circulating beam. With the recent successes obtained in applying this method[6]), it was felt desirable to consider the possibility of extracting particles from other types of machines.

In the regenerative method of particle extraction, a resonance between the radial oscillations of a particle about its equilibrium orbit and the revolutions of the particle about the machine is set up. These oscillations are of definite phase and the amplitudes increase geometrically on successive revolutions. By this means, a large orbit separation on successive revolutions can be obtained, large enough to allow an appreciable fraction of the beam to enter an exit channel. For successful extraction, it is also necessary to require that the amplitude of the vertical oscillations remain bounded.

In general, the frequency of radial oscillations of a particle about its equilibrium orbit is not commensurate with the frequency of rotation of the particle about the machine. In order to achieve the required resonance for the regenerative extraction, one or more sections of the machine are altered by the introduction of a shaped magnetic field perturbation. In the treatment which follows, we shall consider only one such perturbation and refer to it as the regenerator. We shall also assume that the azimuthal size of the regenerator will be small compared to the wavelength of the radial oscillations. Neither of these restrictions are

[1]) Powell, Henrick, Kearns, Sewell, and Thornton, Rev. Sci. Instr. **19** (1948) 506.

[2]) C. E. Leith, Phys. Rev. **78** (1950) 89.

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†† Now at the Radiation Laboratory, University of California, Berkeley, California.

strictly necessary for the successful application of the regenerative process.

As a particle passes through the regenerator, a phase change is introduced in the radial oscillations. With the previous assumptions, this occurs without appreciable change in the displacement of the particle from the equilibrium orbit. This action, therefore, corresponds to a change in the amplitude of the oscillations. If the phase change introduced is such that the next encounter of the regenerator by the particle is in the same phase as the previous one, the amplitude change will be coherent on the successive actions of the regenerator. It can be shown that two possible phases of encounter lead to this phase shift; one corresponds to a decrease in the amplitude of the oscillations, the other to an increase. It can also be shown that, whereas the phase corresponding to the increasing amplitude is stable for errors in the phase of arrival, the other phase is unstable. Eventually, then, the particles will arrive with the stable phase which corresponds to a coherent regenerator action with increasing amplitude.

In order that the regenerator action continue as the oscillations build up in amplitude, it is necessary that the phase change introduced be independent of amplitude. This condition is met by shaping the magnetic field of the regenerator to correspond to a constant n value (or to a constant radial gradient if the regenerator is introduced in a region which is otherwise field free).

For most of the applications which follow, we shall assume that the magnetic field distortion is shaped so as to affect the normal machine fields on only one side of the equilibrium orbit. It is therefore possible, in certain cases, for the regenerative action to occur on other than successive revolutions of the particle about the machine. We shall show that the mode of radial oscillation which corresponds to regenerator action on every other turn of the particle will allow the regenerative extraction of particles from weak focussing machines of the betatron or synchrotron type. The application of this method to extraction of particles from such machines with straight section will also be considered. In a similar manner, extraction from strong focussing machines will be examined, though in somewhat less detail.

2. General Method

In order to investigate the regenerative process, we shall make use of the matrix technique of LeCouteur. In such a formulation, the motion of a particle about the equilibrium orbit can be described by the use of two matrices. These matrices are functions of the machine parameters and will be used to determine allowable extraction schemes. They operate on a vector whose two components are the instantaneous displacement of the particle from its equilibrium orbit and a corresponding velocity. The ratio of these components establishes the phase of the oscillations.

In the special case of a two by two matrix of unit determinant, the eigenvalues of this operation can be expressed directly in terms of the trace of the matrix:

a. If the trace is larger than 2 the eigenvalues are

$$e^{\lambda} \text{ and } e^{-\lambda} \text{ where } 2\cosh\lambda = \text{Trace}; \qquad (1a)$$

b. If the trace is smaller than -2, the eigenvalues are

$$-e^{\lambda} \text{ and } -e^{-\lambda} \text{ where } 2\cosh\lambda = -\text{Trace}; \qquad (1b)$$

c. If the trace is between 2 and -2, the eigenvalues are

$$e^{i\lambda} \text{ and } e^{-i\lambda} \text{ where } 2\cos\lambda = \text{Trace}. \qquad (1c)$$

In the applications which follow, we shall primarily concern ourselves with the real eigenvalues and with the particular case in which the matrix is applied successively a large number of times. The matrices to be used will represent the transformations which correspond to one or more revolutions of a particle in a machine. If the absolute value of the trace is appreciably larger than 2 after a large number of applications of the matrix, the resultant vector will be primarily in the direction of the eigenvector corresponding to the eigenvalue with largest absolute magnitude. The increase in amplitude

of this vector will then be approximately e^{λ} per successive application of the matrix.

This is just the condition we require to build up the amplitude of radial oscillations for beam extraction. However, it is also necessary to require that the amplitude of the vertical oscillations remain bounded. Since the perturbation introduced by the regenerator also affects the vertical oscillations, we must require that the trace of the matrix describing these oscillations remain less than $|2|$. In this case, the regenerator induces changes in the vertical oscillations but does not establish a fixed phase for the oscillations.

LeCouteur has examined the effect of these changes on the oscillations and shows that the root mean square amplitude for the oscillations may be expressed as

$$h^2 = h_0^2 / \sin \varepsilon, \tag{2}$$

where h_0 is the amplitude for the oscillations without the regenerator and h the root mean square amplitude with the regenerator action. The factor $\sin \varepsilon$ is obtained from the transformation matrix by the relationship

$$\sin \varepsilon = \frac{2 \sin \lambda}{\beta\omega - \frac{\gamma}{\omega}}, \tag{3}$$

where the transformation matrix is of the form

$$\begin{pmatrix} \gamma & \beta \\ \gamma & \delta \end{pmatrix},$$

and $2 \cos \lambda = \alpha + \delta$, $2\pi\omega$ is the change in phase of the oscillations between successive applications of the regenerator.

3. Circular Machines

In a circular machine the motion of a particle about its equilibrium orbit may be shown to satisfy the equations

$$\frac{d^2\rho}{d\theta^2} + (1 - n)\rho = 0, \tag{4a}$$

and

$$\frac{d^2z}{d\theta^2} + nz = 0, \tag{4b}$$

where ρ and z are, respectively, the radial and vertical displacements from the equilibrium orbit, θ is the azimuthal angular position of the particle, and n is equal to

$$-\frac{R}{H}\frac{dH}{dr},$$

where R is the radius of the equilibrium orbit.

Solutions to these equations may conveniently be written in the matrix form which displays both the values of the displacement and its derivatives with respect to θ. The values of these quantities are expressed in terms of the values at some other θ by the matrix equations

$$\begin{pmatrix} \rho \\ \dot{\rho} \end{pmatrix}_{\theta} =$$

$$\begin{pmatrix} \cos\sqrt{1-n}(\theta-\theta') & \frac{1}{\sqrt{1-n}} \sin\sqrt{1-n}\theta - \theta' \\ -\sqrt{1-n} \sin\sqrt{1-n}(\theta-\theta') & \cos\sqrt{1-n}(\theta-\theta') \end{pmatrix} \begin{pmatrix} \rho \\ \dot{\rho} \end{pmatrix}_{\theta'}$$

$$= A(\sqrt{1-n}, \theta - \theta') \begin{pmatrix} \rho \\ \dot{\rho} \end{pmatrix}_{\theta'} \tag{5a}$$

and

$$\begin{pmatrix} z \\ \dot{z} \end{pmatrix}_{\theta} = A(\sqrt{n}, \theta - \theta') \begin{pmatrix} z \\ \dot{z} \end{pmatrix}_{\theta'} \tag{5b}$$

where

$$\dot{\rho} = \frac{d\rho}{d\theta} \text{ and } \dot{z} = \frac{dz}{d\theta}.$$

For one complete revolution of the particle, these equations become

$$\begin{pmatrix} \rho \\ \dot{\rho} \end{pmatrix}_{2\pi} = A(\sqrt{1-n}, 2\pi) \begin{pmatrix} \rho \\ \dot{\rho} \end{pmatrix}_{0},$$

and

$$\begin{pmatrix} z \\ \dot{z} \end{pmatrix}_{2\pi} = A(\sqrt{n}, 2\pi) \begin{pmatrix} z \\ \dot{z} \end{pmatrix}.$$

The matrices used to describe one complete revolution in a circular machine containing a regenerator are obtained by substituting for a small sector of the machine a new sector having a value of n different from the rest of the machine. If θ_r is the angular size of the regenerator and n_r the value of n in the regenerator, then the substitution of a regenerator for a sector of the machine corresponds to a multiplicative operation by

$$A^{-1}(\sqrt{1-n}, \theta_r)\, A(\sqrt{1-n_r}, \theta_r),$$

for the radial direction and

$$A^{-1}(\sqrt{n}, \theta_r)\, A(\sqrt{n_r}, \theta_r),$$

for the vertical direction.

To lowest order in θ_r these two expressions reduce to

$$\begin{pmatrix} 1 & 0 \\ -T & 1 \end{pmatrix} = B(-T), \tag{6a}$$

and

$$\begin{pmatrix} 1 & 0 \\ T & 1 \end{pmatrix} = B(T), \tag{6b}$$

respectively, where T, the regenerator strength, is equal to $(n - n_r)\theta_r$.

We may, therefore, write the equations corresponding to one revolution of a particle in a circular machine with one regenerative section as

$$\begin{pmatrix} \rho \\ \dot{\rho} \end{pmatrix}_2 = A(\sqrt{1-n}, 2\pi)\, B(-T) \begin{pmatrix} \rho \\ \dot{\rho} \end{pmatrix}_1, \tag{7a}$$

and

$$\begin{pmatrix} z \\ \dot{z} \end{pmatrix}_2 = A(\sqrt{n}, 2\pi)\, B(T) \begin{pmatrix} z \\ \dot{z} \end{pmatrix}_1, \tag{7b}$$

where the 1 and 2 correspond to the entrance to the regenerator sector on successive turns.

It should, however, be stressed that since the regenerator is located on one side of the equilibrium orbit, only those trajectories which pass through the regenerator should have their corresponding matrices altered in this manner. We shall make use of this property of the regenerator in our subsequent treatment to admit various possible modes of successful extraction.

Matrices A and B both have unit determinants; hence they and all their products satisfy the conditions set forth previously.

Let us assume that a particle passes through the regenerator on a given turn and investigate its radial behavior on subsequent turns. If we assume the transformation matrix is of the form

$$A(\sqrt{1-n}, 2\pi)\, B(-T),$$

then the trace is given by

$$\text{Trace} = 2\cos 2\pi\sqrt{1-n} - \frac{T}{\sqrt{1-n}} \sin 2\pi\sqrt{1-n}. \tag{8}$$

The value of T for which the trace is equal to $+2$ is then given by

$$T_{H1}{}^{+} = -2\sqrt{1-n}\,\frac{1-\cos 2\pi\sqrt{1-n}}{\sin 2\pi\sqrt{1-n}}. \tag{9}$$

For values of T such that

$$T_{H1}{}^{+}(T - T_{H1}{}^{+}) > 0, \tag{10}$$

the trace of the matrix will be larger than 2 and consequently its eigenvalues will be positive. It therefore follows that in order that a particle enter the regenerator on every turn, it is necessary that condition (10) be satisfied. Since the frequency of radial oscillations for the machine, is, in general, incommensurate with the frequency of the circular motion, all particles will eventually be captured in that mode of radial oscillation which enters the regenerator on every turn if the regenerator strength and the value of n allow this. These allowable values of T as a function of n are shown in fig. 1. The shaded region then corresponds to values where the radial oscillations can be built up geometrically to allow radial extraction of the beam of particles. Both positive and negative values of T are considered. In the notation of Tuck and Teng, a regenerator of negative strength is referred to as a peeler.

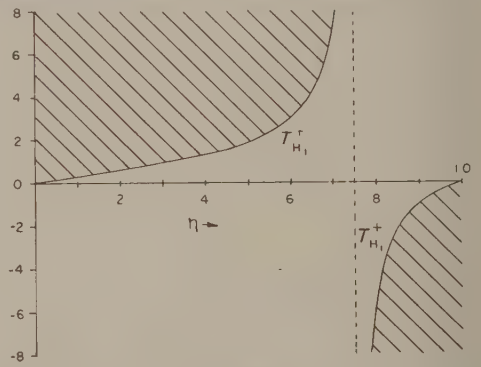

Fig. 1. The shaded regions indicate the values of regenerator strength T as a function of n for which there is an increase in amplitude of radial oscillations.

To investigate the vertical stability in this mode of radial extraction, let us consider the matrix corresponding to the vertical direction with regenerator action on every turn. It is of the form

$$A(\sqrt{n}, 2\pi)\, B(T),$$

and has a trace given by

$$\text{Trace} = 2\cos 2\pi\sqrt{n} + \frac{T}{\sqrt{n}} \sin 2\pi\sqrt{n}. \tag{11}$$

The value of T for which the trace is $+2$ is given by

$$T_{V1}^{+} = 2\sqrt{n}\,\frac{1 - \cos 2\pi\sqrt{n}}{\sin 2\pi\sqrt{n}}. \tag{12}$$

The value of T for which the trace is -2 is given by

$$T_{V1}^{-} = -2\sqrt{n}\,\frac{1 + \cos 2\pi\sqrt{n}}{\sin 2\pi\sqrt{n}}. \tag{13}$$

In order that a particle be stable in the vertical direction, it is necessary that T satisfy the conditions

$$T_{V1}^{\pm}(T - T_{V1}^{\pm}) < 0. \tag{14}$$

The allowable values of T as a function of n are shown in fig. 2.

For successful beam extraction, it is necessary that the conditions expressed by equations (10) and (14) be satisfied simultaneously. This corresponds to the overlap of the shaded areas of figs. 1 and 2. The acceptable region for a radially increasing amplitude with vertical stability is shown in fig. 3. Also included in this figure are values of e^{λ}, the radial increase per turn and sin ε, the parameter measuring the mean square increase in the vertical amplitude, at various points in the allowed region.

In this mode of extraction, values of n larger than 0.25 are not allowed. This mode of extraction is therefore usable for cyclotrons but not for synchrotrons or betatrons which have larger values of n.

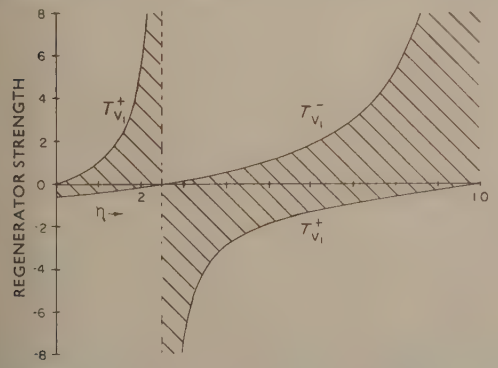

Fig. 2. The shaded regions indicate the values of regenerator strength T as a function of n for which the amplitude of vertical oscillations remains bounded.

We now wish to investigate the possible mode of radial oscillation in which the regenerator is entered only on every other revolution of the particle. In order to be assured that the particle miss the regenerator on the turn after entering it, we need only require that the trace given in eq.

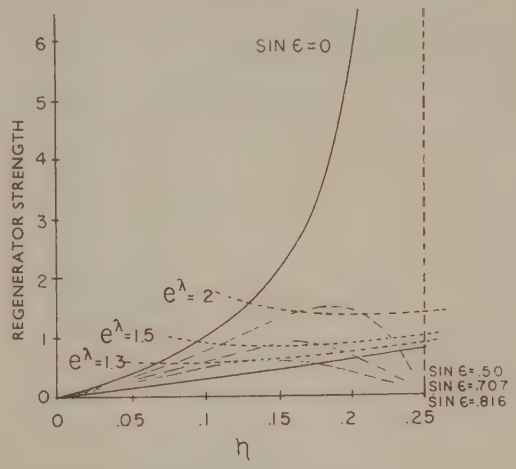

Fig. 3. The allowed values of T as a function of n for successful radial extraction from a circular weak focussing machine when the regenerator acts on every turn. Curves of constant values of e^{λ} and sin ε are shown.

(8) be less than -2. If this is true, a particle with positive (negative) ρ at the regenerator during a given revolution, will have a negative (positive) ρ at the regenerator on the next revolution and hence miss the regenerator. This condition requires that

$$T_{H1}^{-}(T - T_{H1}) > 0, \tag{15}$$

where

$$T_{H1}^{-} = 2\sqrt{1-n}\,\frac{1 + \cos 2\pi\sqrt{1-n}}{\sin 2\pi\sqrt{1-n}}. \tag{16}$$

To investigate this mode of radial oscillation, we therefore consider the matrix for the radial motion in which the regenerator acts on every other turn. It is of the form

$$A(\sqrt{1-n},\, 2\pi)\, A(\sqrt{1-n},\, 2\pi)\, B(-T).$$

The trace of this matrix is given by

$$\text{Trace} = 4\cos^2 2\pi\sqrt{1-n} - 2 - 2T\,\frac{\sin 2\pi\sqrt{1-n}\cos 2\pi\sqrt{1-n}}{\sqrt{1-n}}. \tag{17}$$

The value of T for which the trace is 2 is then given by

$$T_{H2}^{+} = -2\sqrt{1-n}\tan 2\pi\sqrt{1-n}. \tag{18}$$

As before, those values of T satisfying the condition that

$$T_{H2}^{+}(T - T_{H2}^{+}) > 0, \tag{19}$$

lead to matrices of trace larger than 2 and consequently to modes of radial oscillations in which there is a geometrical increase in the amplitudes. Fig. 4 shows the regions allowed for

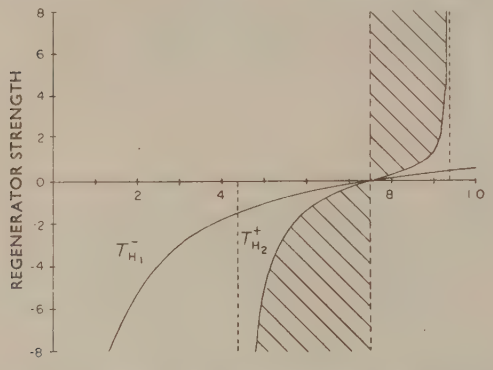

Fig. 4. The shaded region indicates those values of T as a function of n for a weak focussing machine for which the regenerative actions occurs on every other revolution of the particle about the machine

these modes under the restrictions imposed by eqs. (15) and (19).

Investigation of the corresponding matrix describing the vertical motion; i.e.

$$A(\sqrt{n}, 2\pi)\, A(\sqrt{n}, 2\pi)\, B(T),$$

whose trace is

$$4\cos^2 2\pi\sqrt{n} - 2 + \frac{2T \sin 2\pi\sqrt{n} \cos 2\pi\sqrt{n}}{\sqrt{n}}, \tag{20}$$

leads to the conditions

$$T_{V2}^{\pm}(T - T_{V2}^{\pm}) < 0, \tag{21}$$

for vertical stability.
Here

$$T_{V2}^{-} = -2\sqrt{n} \cot 2\pi\sqrt{n}, \tag{22}$$

and

$$T_{V2}^{+} = 2\sqrt{n} \tan 2\pi\sqrt{n}. \tag{23}$$

Fig. 5 shows the region of allowed radial extraction with vertical stability in the mode of radial oscillation in which the regenerator acts every other turn. This region is enlarged in fig. 6 and curves of equal values of e^{λ} and $\sin \varepsilon$ are included.

Extraction of beams from circular machines may, therefore, be accomplished by the regenerative method both for very low values of n, as in the case of cyclotrons, and for values of n in the neighborhood of 0.75. In cyclotrons the equilibrium orbits for various energies are displaced from one another and, therefore, the regenerator may consist of a magnetic bump located just outside the equilibrium orbit of the highest energy particle in the machine.

For betatrons and synchrotrons, where the equilibrium orbit is independent of energy, several possible choices of location are possible. The magnetic field may be altered either radially outward or inward from the equilibrium orbit by a pulsed magnet which would be timed to coincide with the desired extraction energy. Another method would be to locate the magnetic field bump far from the normal equilibrium orbit and alter the radius of the equilibrium orbit at the time of extraction by decreasing or increasing the main magnetic field.

For successful extraction of particles from betatrons and synchrotrons, the values of the

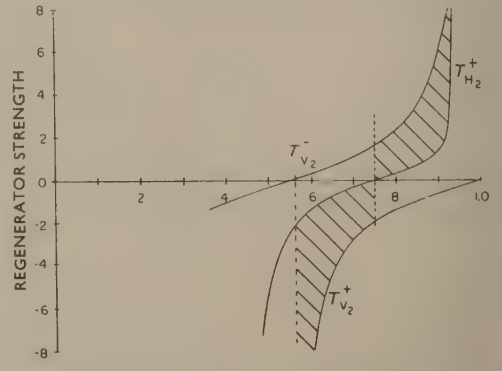

Fig. 5. The shaded indicates the allowed values of T for successful radial extraction for the mode where the regenerator acts on every other revolution of the particle about the machine

regenerator strength, T, are not large. For values of T, comparable with those used in the extraction from synchrocyclotrons, moreover the effects of the regenerator on the vertical oscillations are apparently small.

For example, if we consider a machine which as a value of $n = 0.65$, a regenerator strength of -1.1 (a peeler) will lead to an increase of the radial oscillations of a factor of two per regenerator action. At the same time, the vertical oscillations will have an increase in root mean square amplitude of only 1.5 due to such a regenerator. For a machine of reasonable size, an orbit separation of inches should be attainable.

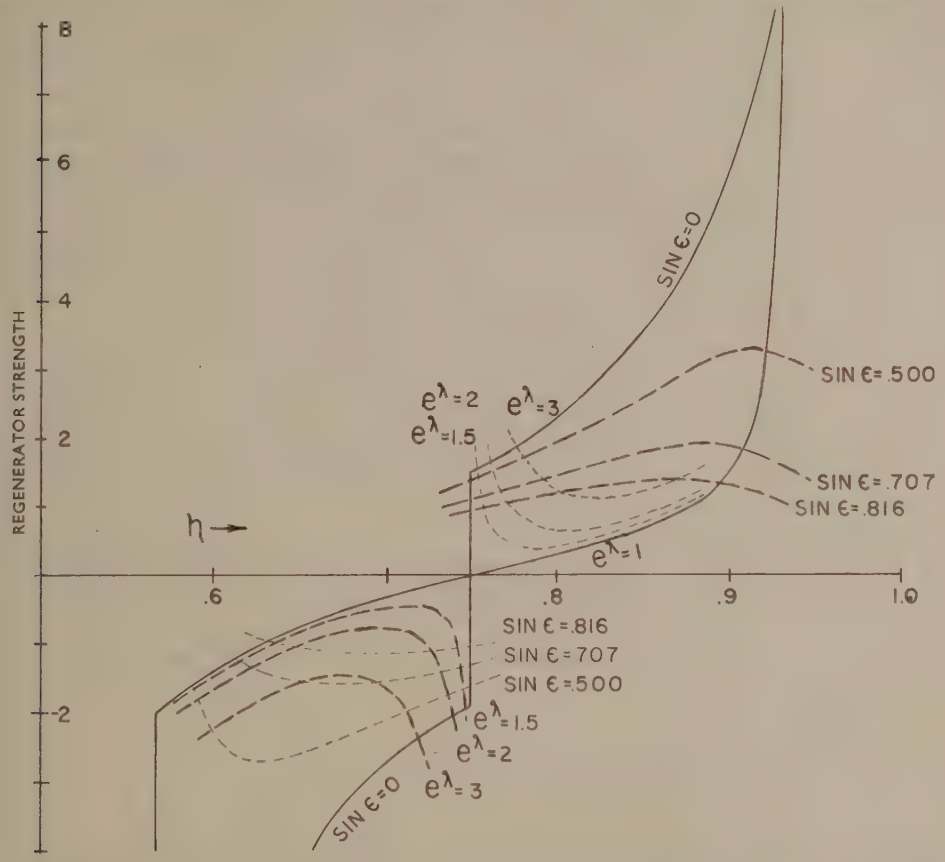

Fig. 6. The allowed reg on of fig. 5 is enlarged and curves of constant values of e^{λ} and sin ε are shown.

4. Weak Focussing Machines with Straight Sections

We shall consider here the possibility of radial extraction from a weak focussing machine containing several straight sections. In particular, we shall consider specifically a machine with straight sections of equal length. The extension of the technique to machines with unequal straight sections is apparent.

The trajectory of a particle passing through a straight section of length L may be described by the matrix equations

$$\begin{pmatrix} \rho \\ \frac{d\rho}{dx} \end{pmatrix}_{out} = \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix} \begin{pmatrix} \rho \\ \frac{d\rho}{dx} \end{pmatrix}_{in},$$

and

$$\begin{pmatrix} z \\ \frac{dz}{dx} \end{pmatrix}_{out} = \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix} \begin{pmatrix} z \\ \frac{dz}{dx} \end{pmatrix}_{in},$$

For our purposes, these may be expressed as

$$\begin{pmatrix} \rho \\ \dot{\rho} \end{pmatrix}_{out} = \begin{pmatrix} 1 & L/R \\ 0 & 1 \end{pmatrix} \begin{pmatrix} \rho \\ \dot{\rho} \end{pmatrix}_{in} = C(L/R) \begin{pmatrix} \rho \\ \dot{\rho} \end{pmatrix}_{in}, \quad (24a)$$

and
$$\begin{pmatrix} z \\ \cdot \\ z \end{pmatrix}_{\text{out}} = C(L/R)\begin{pmatrix} z \\ \cdot \\ z \end{pmatrix}_{\text{in}}, \tag{24b}$$

where R is the radius of curvature of the equilibrium orbit in a magnet section.

The traversal of one straight section followed by one magnet section is described by the equations

$$\begin{pmatrix} \rho \\ \cdot \\ \rho \end{pmatrix}_{\text{out}} = A(\sqrt{1-n},\, 2\pi/m)\, C(L/R)\begin{pmatrix} \rho \\ \cdot \\ \rho \end{pmatrix}_{\text{in}} =$$

$$D(L/R, \sqrt{1-n},\, 2\pi/m)\begin{pmatrix} \rho \\ \cdot \\ \rho \end{pmatrix}_{\text{in}} = D_H\begin{pmatrix} \rho \\ \cdot \\ \rho \end{pmatrix}_{\text{in}}, \tag{25a}$$

and
$$\begin{pmatrix} z \\ \cdot \\ z \end{pmatrix}_{\text{out}} = D(L/R, \sqrt{n},\, 2\pi/m)\begin{pmatrix} \tilde{\epsilon} \\ \cdot \\ z \end{pmatrix}_{\text{in}} = D_V\begin{pmatrix} z \\ \cdot \\ z \end{pmatrix}_{\text{in}}, \tag{25b}$$

where m is the number of magnet sections in the machine.

If we assume the machine is made up of m such sections, and hence that all straight sections are equal, the equations describing one complete revolution starting from the entrance to one of the straight sections are given by

$$\begin{pmatrix} \rho \\ \cdot \\ \rho \end{pmatrix}_{2\pi} = D_H^m\begin{pmatrix} \rho \\ \cdot \\ \rho \end{pmatrix}_0, \tag{26a}$$

and

$$\begin{pmatrix} z \\ \cdot \\ z \end{pmatrix}_{2\pi} = D_V^m\begin{pmatrix} z \\ \cdot \\ z \end{pmatrix}_0. \tag{26b}$$

The matrices in these equations may be simplified and shown to satisfy the relationship

$$D_i^m = a^i{}_m D_i - a^i{}_{m-1} \cdot 1, \tag{27}$$

where the a_{mj}'s are functions of the trace of D_i and given by the recursion relationship

$$a^i{}_{m+1} = a^i{}_m \,\text{Trace}\,(D_i) - a^i{}_{m-1} \tag{28}$$

$$a^i{}_0 = 0 \qquad a^i{}_1 = 1.$$

We may, therefore, rewrite the above as

$$\begin{pmatrix} \rho \\ \cdot \\ \rho \end{pmatrix}_{2\pi} = (a^H{}_m D_H - a^H{}_{m-1})\begin{pmatrix} \rho \\ \cdot \\ \rho \end{pmatrix}_0, \tag{29a}$$

and

$$\begin{pmatrix} z \\ \cdot \\ z \end{pmatrix}_{2\pi} = (a^V{}_m D_V - a^V{}_{m-1})\begin{pmatrix} z \\ \cdot \\ z \end{pmatrix}_0, \tag{29b}$$

Two possible choices of regenerator location exist in a machine of this type. It may be located in the straight section or in a magnet section. We shall assume here that the regenerator is located at the entrance to one of the straight sections of the machine. This choice of position for the regenerator is arbitraty and made here only for mathematical convenience. Similar treatments could be carried out for any location of the regenerator section.

If we replace a straight section of length l by a section in which there is a uniform radial gradient of the magnetic field starting at the equilibrium orbit, matrices corresponding to this substitution will be

$$\begin{pmatrix} 1 & l/R \\ 0 & 1 \end{pmatrix}^{-1}\begin{pmatrix} \cos Kl & \dfrac{1}{KR}\sin Kl \\ -KR\sin Kl & \cos Kl \end{pmatrix},$$

for the radial direction and

$$\begin{pmatrix} 1 & l/R \\ 0 & 1 \end{pmatrix}^{-1}\begin{pmatrix} \cosh Kl & \dfrac{1}{KR}\sinh Kl \\ KR\sinh Kl & \cosh Kl \end{pmatrix},$$

for the vertical direction, where k^2 is equal to

$$\frac{1}{H_0 R}\frac{\mathrm{d}H}{\mathrm{d}r},$$

R is the radius of curvature of the equilibrium orbit in a magnet section and H_0 the magnetic field along this orbit.

In the limit of small l these reduce to

$$B\,(-T), \tag{30a}$$

and

$$B\,(T), \tag{30b}$$

respectively, where

$$T = -k^2 Rl = -\frac{l}{H_0}\frac{\mathrm{d}H}{\mathrm{d}r}. \tag{31}$$

The matrix equations describing one revolution about a machine with such a regenerator in place and with regenerative action are

$$\begin{pmatrix} \rho \\ \cdot \\ \rho \end{pmatrix}_2 = (a^H{}_m D_H - a^H{}_{m-1})\, B(-T)\begin{pmatrix} \rho \\ \cdot \\ \rho \end{pmatrix}_1, \tag{32a}$$

and

$$\begin{pmatrix} z \\ \cdot \\ z \end{pmatrix}_2 = (a^V{}_m D_V - a^V{}_{m-1})\, B(T)\begin{pmatrix} z \\ \cdot \\ z \end{pmatrix}_1, \tag{32b}$$

where the values of ρ and z are measured at the entrance to the regenerator.

The radial motion after one such traversal of the regenerator is investigated as in our previous

example. The value of T for which the trace of the matrix is 2 is given by

$$T_{H1^+} = -\frac{2 + 2\,a^{H}{}_{m-1} - \text{Trace}\,(D_H)\,a^{H}{}_{m}}{\beta^{H} a^{H}{}_{m}}, \tag{33}$$

where β^H is the upper right element of the transformation matrix D_H.

If

$$T_{H1^+}\,(T - T_{H1^+}) > 0, \tag{34}$$

then particles will increase in radial amplitude on successive turns about the machine. At the same time, in order to insure vertical stability, we must require that

$$T_{V1^\pm}\,(T - T_{V1^\pm}) < 0, \tag{35}$$

where

$$T_{V1^\pm} = \frac{2a_{Vm-1} - \text{Trace}\,(D_V)a^{V}{}_{m} \pm 2}{\beta^{V} a^{V}{}_{m}}. \tag{36}$$

If these conditions are satisfied, extraction of the particles by means of the mode of radial oscillation in which the regenerator acts on every turn is then possible.

For the extraction process in the mode in which the regenerator acts on every other turn, the conditions to be satisfied are

$$T_{H1^-}\,(T - T_{H1^-}) > 0, \tag{37}$$

$$T_{H2^+}\,(T - T_{H2^+}) > 0, \tag{38}$$

and

$$T_{V2^\pm}\,(T - T_{V2^\pm}) < 0, \tag{39}$$

where these quantities are defined by

$$T_{H1^-} = -\frac{2a^{H}{}_{m-1} - \text{Trace}\,(D_H)a^{H}{}_{m} - 2}{a^{H}{}_{m}\beta^{H}}, \tag{40}$$

$$T_{H2^+} = -\frac{2a^{H}{}_{2m-1} - \text{Trace}\,(D_H)a_2{}^{H}{}_{m} + 2}{a^{H}{}_{2m}\beta^{H}}, \tag{41}$$

and

$$T_{V2^\pm} = \frac{2a_{V2m-1} - \text{Trace}\,(D_V)a^{V}{}_{2m} \pm 2}{a^{V}{}_{2m}\beta^{V}}. \tag{42}$$

Since eqs. (37) through (42) involve several parameters, no general limits on the allowed values of the regenerator strengths can be given. However, for a given machine, the matrices can be determined and numerical values for the above equations can be obtained.

5. Strong Focussing Machines

The analysis of a regenerative extraction process for strong focussing machines can be carried out in much the same manner as that of the previous section. Since the radial and vertical frequencies are however not related simply, the investigation of the proper mode for extraction must be carried out for each machine separately. If it is found that the mode in which the regenerator acts on every turn is a proper mode for extraction, it is not necessary to restrict the magnetic field alteration to one side of the equilibrium orbit. It is therefore possible to use a quadrupole lens as a regenerator in such a case.

6. Phase Determinations

The phase of the radial oscillation at the entrance to the regenerative section for all of the machines discussed can most easily be determined by use of a phase diagram. We shall measure the phase from the node of the oscillation. Fig. 7 shows a phase plot for the situation in which coherent regenerative action with increasing amplitude is taking place. Here $\Delta\phi$

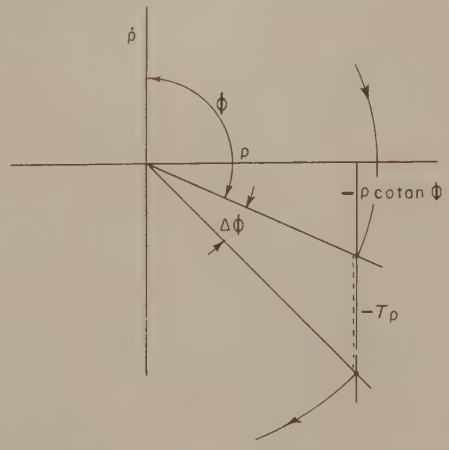

Fig. 7. A phase plot showing the action of the regenerator in the phase stable situation. ρ is the displacement from the equilibrium orbit at the regenerator and ϕ is the phase of the oscillation measured from the node. $\Delta\phi$ is the phase defect which must be supplied by the regenerator to produce resonance. The regenerative action is indicated by the dotted line and is shown to be proportional to T, the regenerator strength.

the phase defect, is the change of phase which the regenerator must supply to lead to the required resonance. The phase at the entrance can then be expressed in terms of the regenerator strength T and the phase defect $\Delta\phi$ by the equation

$$\frac{1}{T \sin^2 \phi} - \cot \phi = \cot \Delta\phi.$$

For a weak focussing machine $\Delta\phi$ is

$$2\pi (1 - \sqrt{1 - n})\, S ,$$

where s is the number of turns between successive applications of the regenerator.

7. Discussion

We have shown that regenerative beam extraction is possible in a variety of different machines. In particular, the application to betatrons and synchrotrons seems quite straightforward. In these cases, the use of one regenerator is sufficient. However, for weak focussing machines with straight sections or strong focussing machines it is possible that neither single nor double turn extraction will be feasible. Recourse may then be had by either multiple turn extraction or the use of more than one regenerator element.

It is conceivable that a similar mechanism to the one discussed above could be of use while injecting particles into a ring-shaped machine[7]). In this case, one would inject at such a phase that the negative exponential solution dominates. As we have seen, though, this solution is not phase stable so that the positive exponential solution would soon predominate and the particles would be ejected from the machine again. A careful adjustment of the injection phase and control of the angular spread of the injected particles will, however, allow a considerable damping of the radial oscillations before they begin to increase. The regenerator must be made inoperative before this increase occurs.

We would like to express our gratitude to Kirk Dickens for his assistance in the laborious computations which have been necessary to prepare this paper.

[7]) Lee C. Teng, Phys. Rev. **100** (1955) 1247.

NUCLEAR INSTRUMENTS 1 (1957) 41–45; NORTH-HOLLAND PUBLISHING CO. – AMSTERDAM

A PROPORTIONAL COUNTER SYSTEM WITH SMALL WALL EFFECT

R. W. P. DREVER, A. MOLJK and S. C. CURRAN†

Department of Natural Philosophy, University of Glasgow

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The wall effects interfering with low energy measurements with proportional counters using gaseous sources are discussed, and a new type of counter in which they are considerably reduced is described. A layer of gas surrounding the sensitive volume is turned into a separate detector by a multiwire counting system which prevents escaping electrons or X-rays being registered. Applications to a new measurement of the L/K-capture ratio of ^{71}Ge, and to low level counting, are described.

1. Introduction

Proportional counters have been extensively employed for low energy beta spectroscopy[1,2] since with sources in suitable gaseous form, as part of the filling, backscattering and absorption errors are avoided. Measurements can therefore extend to energies lower than can be reached with other types of spectrometer. The 4π geometry gives high counting efficiency and the resulting integration of simultaneous radiations facilitates studies of orbital electron capture. These features of the proportional tube spectrometer often compensate for the relatively poor energy resolution, though in fact it is the worsening of the resolution, as the number of ion pairs produced by the primary particle decreases, that sets a practical limit to the energy region of the instrument at about 150 eV.

The possibility of counting relatively large samples efficiently makes proportional counters useful also for measurements of weak radioactivity when suitable gases are available. This technique is widely used for radiocarbon dating.

In all investigations involving gaseous sources, effects due to the wall of the counter must be considered. A beta spectrum, for example, is given correctly by the observed pulse height distribution only if the electrons spend all their energy in the sensitive volume of the counter. With a gaseous source this condition can only be satisfied approximately. For a counter of radius r, a fraction $2R(1 - R/2r)/r$ of the source is within a distance R from the wall of the counter. One quarter at least of the electrons of range R emitted in this region will escape without spending their total energy in the gas and will be incorrectly registered as electrons with lower energy. Thus the low energy part of a beta spectrum will be distorted, and other low energy phenomena may be obscured, unless the diameter of the counter is large compared with the range of the highest energy electrons emitted.

In studies of electron capture similar effects due to the escape of K X-rays may lead to errors in measurements of both K and L-capture intensities.

In addition to escape through the cylindrical wall of the counter particles can enter, as well as leave, the sensitive volume at both ends. Since the length of a counter is usually much greater than its radius, and can in any case easily be increased, this end effect is relatively unimportant.

Wall effects can in principle be made small by using a sufficiently large counter or high pressure, in some cases together with a magnetic field applied in the axial direction. However

[1]) D. West, Progress in Nuclear Physics 3 (1953) 18.

[2]) S. C. Curran, in Beta and Gamma-Ray Spectroscopy edited by K. Siegbahn (North-Holland Publishing Company Amsterdam 1955).

† now at U. K. Atomic Energy Authority, Aldermaston, Berkshire, England.

practical limitations are set by purity of the gas, background counting rate, and the high voltage required to give a large enough electrical field strength near the wall.

An alternative method of solving the problem is to detect the particles that escape from the counter and exclude them from the measurements. This could be done if the cathode of the counter were transparent to electrons and surrounded by a second counter system in anticoincidence. It has been found possible to build such an arrangement using two circular arrays of wires to form both the cathode of the main counter and the outer counter units. The layer of gas surrounding the central counter is thus turned into a separate detecting medium.

With this counting system all beta particles are recorded with correct energy, and escaping high energy particles have no effect on the low energy part of the measured spectrum. Although the effective sensitive volume now depends on energy, the dimensions of the main counter need only be large compared with the range of the electrons that are actually being investigated. The main effects of the counter walls on low energy measurements are avoided, and, for brevity, the whole arrangement will be referred to as a *wall-less counter*.

This type of counter is also suitable for other purposes, such as the measurement of sources of low activity. In this case the background counting rate due to cosmic rays and radioactive contamination has to be kept as low as possible. A wall-less counter is insensitive to charged particles from outside and since charged primary and secondary particles account for the major part of the background it can be used with advantage as will be seen later.

2. Design of Wall-less Counters

A wall-less counter that has proved satisfactory is shown in figs. 1 and 2. The cathode of the main counter consists of stainless steel wires, 0.2 mm in diameter, connected to the case. These wires also form part of the cathode of the

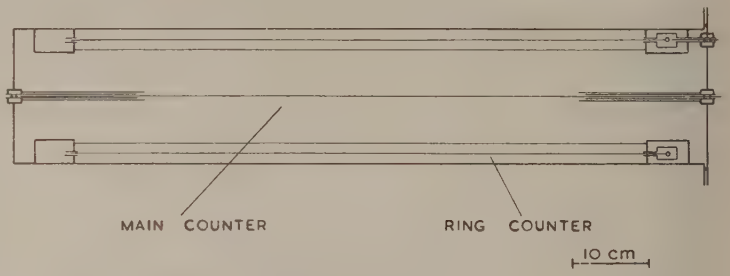

Fig. 1. Arrangement of a wall-less counter.

ring counters, whose anodes are the 0.07 mm alternate wires of the outer circle. Further cathode wires are mounted between the counting wires so that near the anode of each counting unit the field distribution is almost the same as in a normal counter. The wires, kept taut by individual springs, are mounted in a structure designed so that the whole ring system can be removed from the counter as a unit. The counting wires are fitted with guard tubes and

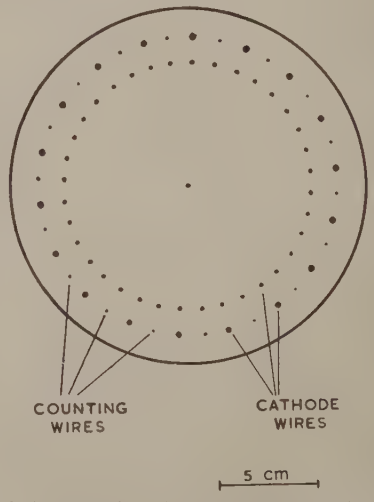

Fig. 2. Cross section of the counter shown in fig 1.

connected together inside the vessel. The main counter has field correcting tubes as well as guard tubes.

For beta spectroscopy and counting a thin detecting layer around the main counter might be preferable to ensure efficient use of the

source. However as the thickness is reduced, more counting wires are required, giving higher

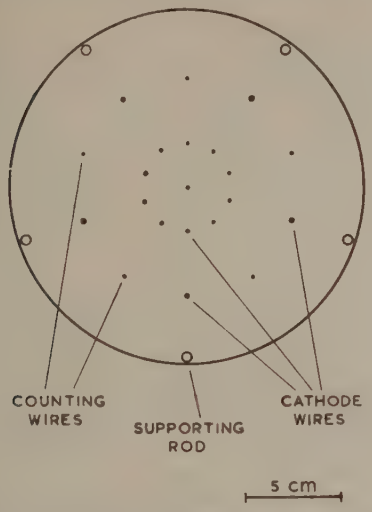

Fig. 3. Cross section of a counter used in the measurement of the L/K-capture ratio of ^{71}Ge.

capacity and thus making the output pulses smaller. This, together with the small energy loss of a fast particle in a thin layer of gas, sets a lower limit to the practicable thickness of the ring counter. A high gas multiplication is needed in any case since in a counter such as that in fig. 1 with a ring 2.5 cm thick and an argon-methane filling at 1 atm the minimum energy loss of high energy electrons crossing the ring is 9 keV, and with 18 counting wires this gives a pulse which in a single counter would be equivalent to only 500 eV.

For electron capture studies different considerations determine the size of the ring system since efficient detection of X-rays is required. A thick ring system along with high pressure may therefore be necessary. A cross section of a counter of this type for use at a pressure of 6 atm is shown in fig. 3.

3. Operation and Characteristics

A simplified block diagram showing the arrangement of the equipment used with these wall-less counters is given in fig. 4. Pulses from the main counter are amplified, delayed and passed through a linear gate circuit to a pulse height analyser. The amplified pulses from the ring counters are lengthened and control the gate. It was found important that both amplifiers have good non-overload characteristics.

The central wire is kept at earth potential and the case is connected to a negative high voltage supply. A low voltage is applied to the anodes of the ring counters to enable separate adjustment of the gains in the central and ring counter systems.

Both the central and the ring counter have been found to operate satisfactorily, even at high gain. The performance of a multiwire ring counter itself is indicated by the pulse height distribution in fig. 5 due to the 10.2 keV K-capture radiation from a ^{71}Ge H_4 gaseous source.

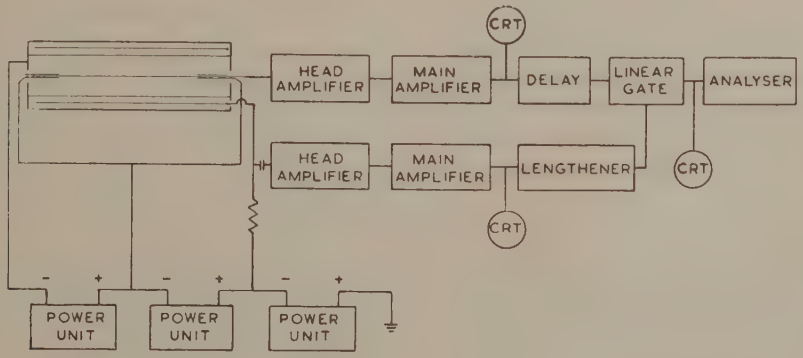

Fig. 4. Block diagram of the electronic equipment.

It is evident that the unusual cathode structure does not affect the resolution seriously and that variations in gain between individual counting units are negligible.

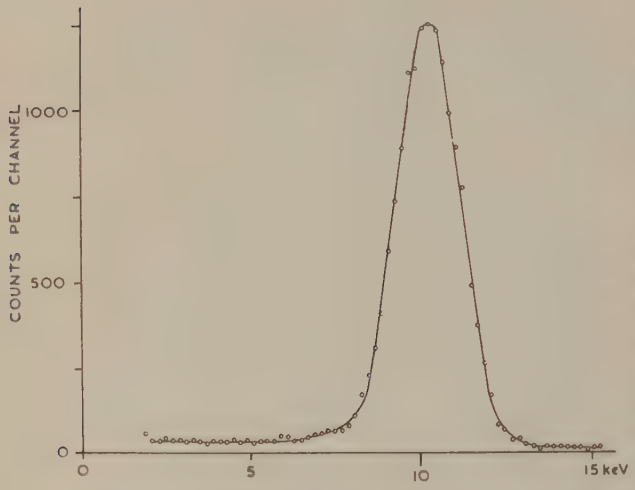

Fig. 5. Pulse distribution from the ring counter of fig. 3 showing the K-capture peak from a ^{71}Ge gaseous source.

The ring counters are used in the proportional region as well as the main counter so there is no coupling through photons produced in the avalanche. However the central and the ring counters are not completely electrically independent since in spite of the screening by the cathode wires the movement of positive ions in the main counter which causes the observed pulse also induces a smaller pulse of opposite sign on the anode wires of the ring counter. Since the positive ions are effective only when close to the anode, the ratio of the charges induced on the central wire and on the ring wires is approximately equal to the ratio of the mutual capacity between the wires, to the capacity between the exposed length of the central wire and the cathode.

For the counter shown in fig. 1 the mutual capacity is 0.3 pF while the capacity of the exposed central wire is 5 pF. Taking into account capacities to earth, the voltage of the induced pulse is 1/80 th of the voltage of the original pulse on the central wire, as was verified by direct measurement. This coupling effect is thus small and since the induced pulses are of the opposite sign to normal ones it does not affect counting.

4. Applications

The wall-less counters described here have proved to be entirely practicable and have already shown their value in some recent experiments. These applications as well as some others will now be briefly discussed.

4. 1. ELECTRON CAPTURE

The X-rays and Auger electrons following electron capture can be measured directly with a normal proportional counter using a gaseous source and this technique has been employed in several determinations of ratios of K-capture to positron emission and of L/K-capture ratios. When beta emission is present the use of a wall-less counter enables the resultant coninuous background to be much reduced and the areas of X-ray peaks can then be measured more accurately. In addition if the thickness of the detecting ring is made large compared with the halfthickness for absorption of X-radiation in the gas, errors due to escape of X-rays are almost eliminated. The actual counting volume can be regarded as a small sample in an effectively infinite volume of gas, and photons entering the central counter from the ring compensate for those leaving it. In such a wall-less counter the X-ray escape correction is thus considerably smaller than in a normal proportional counter of the same overall dimensions. This becomes evident when it is considered that none of the effective part of the source is near the wall.

Recently the L/K-capture ratio in germanium 71, a pure electron capture source without associated gamma rays, has been measured with this technique[3]). Previous work with a normal proportional counter[4]) gave an L/K-capture ratio of 0.30 which is in considerable disagreement with the theoretical value of 0.10. However the observed L-peak was due mainly to the detection of L-radiation emitted simultaneously

[3]) R. W. P. Drever and A. Moljk, to be published elsewhere.

[4]) M. Langevin, Compt. Rend. **39** (1954) 1625.

with escaping K X-rays following K-capture and only partly due to L-capture itself. The correction for this effect depends strongly on the fluorescence yield which is not known accurately enough. Taking a more recently[5]) suggested value for the fluorescence yield of 0.50, instead of 0.45, changes the L/K-capture ratio from 0.30 to 0.19. A method which does not involve such critical corrections would be preferable.

A wall-less counter like that in fig. 3, with a sensitive length of 16 cm, has been used to reinvestigate the decay. In a filling of argon at 6 atms together with 15 cm of methane and a trace of GeH_4 source, the halfthickness for the 9.2 keV K X-rays of 0.8 cm is small compared with the thickness of the ring counter so almost all escaping X-rays are detected and any simultaneous L-pulses are rejected. Corrections required for X-rays escaping undetected through the end of the counter and those absorbed in the cathode wires are relatively small and the total correction to the final result is only 5%. The L/K-capture ratio obtained in this way is 0.128.

4. 2. MEASUREMENT OF GASEOUS SOURCES OF LOW SPECIFIC ACTIVITY

Proportional counters for low activity measurements are normally surrounded by a ring of Geiger counters connected in anticoincidence with the main counter so that charged cosmic ray particles are not recorded, and heavy shielding is used to reduce gamma flux. It is clear that a wall-less counter like that in fig. 1 can replace this arrangement since it is insensitive to charged cosmic ray particles, with the possible exception of those which come through the unshielded ends. However one end can be readily protected by dividing the central wire into two separate parts joined by a glass head near one end of the counter, and connecting the short counter thus formed in parallel with the ring counters.

A counter of this type with the same dimensions as that in fig. 1 has been built with application to radiocarbon dating particularly in mind[6]). For this purpose high counting efficiency over the energy region of the carbon 14 beta spectrum, which has an end point of 156 keV, is required. A magnetic field of 1500 Gauss is applied parallel to the axis to reduce the number of electrons crossing the boundary between the centre and ring counters. Background measurements show that the shielding counter system is very efficient since the component of the background counting rate due to charged particles entering the counter is less than 1.3 counts/min in the energy region between 4 and 150 keV, while the corresponding counting rate without anticoincidence is 460 counts/min.

This counter has the further advantage that it is less sensitive to gamma radiation than the usual arrangement. In a normal counter the detection of gamma rays takes place mainly through the production of secondary electrons in the wall and this is eliminated here. As a result this wall-less counter with a sensitive volume of 5.5 l has a background of only 2.2 counts/min at 1 atm, which is lower than that of other counters of similar counting volume.

The applications of the wall-less type of proportional counter mentioned above show that in spite of its apparent complexity it is a practical instrument that can remove some of the difficulties in measurements involving gaseous sources.

One of the authors (A. M.) would like to thank Professor P. I. Dee for his encouraging hospitality and the University of Ljubljana for leave of absence, while one of the authors (R. W. P. D.) is indebted to the Department of Scientific and Industrial Research for a financial grant.

[5]) B. L. Robinson and R. W. Fink, Rev. Mod. Phys. 27 (1955) 424.

[6]) A. Moljk, R. W. P. Drever and S. C. Curran, to be published elsewhere.

NUCLEAR INSTRUMENTS 1 (1957) 46–52; NORTH-HOLLAND PUBLISHING CO. – AMSTERDAM

ABERRATIONS AND FRINGING EFFECTS IN A 180° DOUBLE FOCUSSING MAGNETIC SPECTROMETER

DAVID L. JUDD and SIDNEY A. BLUDMAN

Radiation Laboratory, University of California Berkeley, California

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Second and third order effects, including fringing, are considered for a 180° symmetrical double focussing spectrometer. The optic axis and focal points for particles of a definite momentum are found. Values are calculated for β and γ, the coefficients of the quadratic and cubic terms in the expansion of the magnetic field, which eliminate second and third order aberrations due to radial motion. The linear dispersion and the orientation of the focal plane for paraxial trajectories of slightly different momenta are determined. Numerical values are presented for a high transmission alpha-particle spectrometer designed for this laboratory.

1. Introduction

Several years ago one of us[1]) investigated some of the lowest order magneto-optical properties of a class of magnetic spectrometers generalized from that proposed by Siegbahn and Svartholm[2]). In these instruments one or both of the conjugate foci may lie outside the region of magnetic field, and it was recognized that the treatment of paraxial rays, to determine the Gaussian optics of the system, could not be extended to calculate aberrations without at the same time including a discussion of the effects on the trajectories of magnetic fringing where the particles enter and leave the field. This paper is devoted to an examination of the second order aberrations and of fringing effects of comparable magnitude, together with some calculations relating to third order aberrations. This work was undertaken in connection with the design and construction of a 180° symmetrical double focussing alpha-particle spectrometer by F. Asaro and I. Perlman at this laboratory, and many of our calculations are specialized to this case. This instrument is now complete but is still undergoing tests to determine its optical quality. Its properties will be reported at a later date.

[1]) D. L. Judd, Rev. Sci. Instr. **21** (1950) 213.

[2]) K. Siegbahn and N. Svartholm, Nature **157** (1946) 872; Ark. f. Mat. Astr. o. Fys. **33A** (1946) no. 21.

2. Scope of the Present Calculations

In building a 180° double-focussing magnetic spectrometer it is simplest to construct the magnet poles of exactly semicircular shape, with a gap separation depending only on the radial distance r from the axis of symmetry in cylindrical coordinates r, θ, z. This will generate a magnetic field symmetric about $z = 0$, the midplane between the poles, and independent of the azimuth θ well inside the poles. Near $\theta = \pm 90°$, in the fringing region, the magnetic field decreases to zero continuously over a distance of the order of magnitude of the pole gap. Neglecting the finite extent of the fringing field and considering only paraxial rays, the optic axis of the system consists of the semicircle $r = R$, $z = 0$, inside the field $|\theta| \leqslant \pi/2$ and of the rectilinear extensions of this semicircle outside the pole edges. The theory of paraxial rays[1]) shows that, if the field inside the poles is shaped so that $H_z(r) = H_0(1 - \frac{1}{2}\rho + \ldots)$ in the midplane ($\rho \equiv (r - R)/R$, $H_0 \equiv (p_0 c)/(eR)$), then a point source of monoenergetic charged particles of momentum p_0 and charge e, placed on the optic axis outside the field, will produce a paraxial point image. Source and image will be symmetrically located if each lies a distance $d_0 = 2^{\frac{1}{2}} \cot (2^{-3/2}\pi)$ beyond the pole edges. If the source emits particles of slightly different

momentum $p \equiv p_0(1 + \Delta)$ the paraxial image will be displaced by a distance $4R\Delta$ normal to the optic axis.

In order to determine and optimize the resolution attainable with such a spectrometer, it is necessary to calculate the size and shape of the image produced by a pencil of rays occupying a finite solid angle. This involves expanding the field and the equations of the trajectories to include terms of second order in the displacements normal to the optic axis, and then selecting the second field shape parameter β in the expansion

$$H_z(r)\,|_{z=0} = H_0(1 - \tfrac{1}{2}\rho + \beta\rho^2 + \gamma\rho^3 + \cdots)$$

so as to minimize the resulting image size. It is known that it is impossible to select β so as to reduce both dimensions of the image to zero to second order, but is is of greater importance to eliminate aberrations in the radial direction than those normal to it, since a line image of a point source, oriented normal to the direction of dispersion, is acceptable. Furthermore, it is convenient to achieve a solid angle of acceptance large enough to be useful by admitting a pencil of rays having a radial extent an order of magnitude larger than its axial height; thus aberrations due to displacements in z are intrinsically much smaller than radial aberrations. We have therefore calculated and eliminated aberrations in the plane $z = 0$ and estimated the effects of z displacements on the image size and shape.

Since it is desired to use as wide a radial aperture as possible we will also calculate third order terms in the displacements so as to arrive at an optimum value of γ, the third order field shape parameter, which will eliminate aberrations of the corresponding order in the plane. In a careful treatment of this plane problem, it is necessary to take account of the effects of fringing. The fringing effects will be measured by a parameter a, defined as the distance along the optic axis over which the fringing field falls by an order of magnitude, measured in units of R. The effects of fringing are as follows. (1) The optic axes outside the magnet are bent through equal angles of order a, bringing image and object closer to each other. (2) The symmetrical paraxial conjugate foci (source and image points) are moved along the optic axis by a distance of order a. (3) The optimum values of β, γ, ... (defined as those eliminating aberrations in the midplane for $\Delta = 0$) are altered from their values in the absence of fringing by amounts of order a. Each of these effects may be expanded in a power series in a, the coefficients involving integrals of the field shape in the fringing region. Effects (1) and (2) are of no importance in magnet design, but the focussing effect (3) leads to a description of the midplane field shape as follows:

$$H_z(r)\,|_{z=0} = H_0\,[1 - \tfrac{1}{2}\rho + (\beta_0 + \beta_1 a + \beta_2 a^2 + \cdots)\rho^2 + (\gamma_0 + \gamma_1 a + \cdots)\,\rho^3 + (\delta_0 + \cdots)\,\rho^4 + \cdots].$$

Since ρ and a are both regarded as small quantities, it is consistent to evaluate β_0, β_1, γ_0 but not β_2, γ_1, or to evaluate β_0, β_1, β_2, γ_0, γ_1, δ_0 but not β_3, γ_2, δ_1, etc. In this paper we make the former choice, since β_2 depends in a very detailed way on the shape of the fringing field. (It should also be noted that, under the assumptions made above, a will be considerably smaller than the largest values of ρ we hope to use, so that in future work it would be more important to evaluate δ_0 and γ_1 than to determine β_2.)

3. Trajectory Calculations inside the Magnet

We use the cylindrical coordinates introduced above in the region where the field has axial symmetry, and choose units of length, field strength, and momentum such that $R = H_0 = p_0 = 1$. The exact orbit equations then are

$$(1 + \rho)\,\rho'' - 2\rho'^2 - (1 + \rho)^2 = [(1 + \rho)^2 + \rho'^2 + z'^2]^{\frac{1}{2}}\,\{-[(1 + \rho)^2 + \rho'^2]\,H_z + \rho' z' H_r\}\,(1 + \Delta)^{-1},$$

$$(1 + \rho)z'' - 2\rho' z' = [(1 + \rho)^2 + \rho'^2 + z'^2]^{\frac{1}{2}}\,\{[(1 + \rho)^2 + z'^2]H_r - \rho' z' H_z\}\,(1 + \Delta)^{-1},$$

where primes denote differentiations with respect to θ. The sign of the magnetic field has

been chosen so that a positively charged particle will move in the direction of increasing θ. The field components H_z and H_r are related by $\nabla \cdot \vec{\mathbf{H}} = \nabla \times \vec{\mathbf{H}} = 0$, and can be expanded about the reference circle as follows:

$$H_z = [1 - \tfrac{1}{2}\rho + \beta\rho^2 + \gamma\rho^3 + \cdots]$$
$$+ z^2[(\tfrac{1}{4} - \beta) + (-\tfrac{1}{4} - \beta - 3\gamma)\rho + \cdots] + \cdots,$$
$$H_r = z[-\tfrac{1}{2} + 2\beta\rho + \cdots] + \cdots.$$

This scheme may be readily continued by use of the definitions

$$H_z = \sum_{k \geq 0} \sum_{l \text{ even}} A_{kl}\rho^k z^l,$$
$$H_z = \sum_{k \geq 0} \sum_{l \text{ odd}} C_{kl}\rho^k z^l,$$
$$A_{00} = 1, \qquad A_{10} = -\tfrac{1}{2},$$
$$A_{20} = \beta, \qquad A_{30} = \gamma,$$
$$C_{00} = 0, \qquad A_{kl} = 0 \text{ for } k < 0,$$

and the relations

$$(l+1)C_{k,l+1} = (k+1)A_{k+1,l} \qquad (\text{even } l)$$
$$(k+1)(C_{kl} + C_{k+1,l}) =$$
$$-(l+1)(A_{k-1,l+1} + A_{k,l+1}) \qquad (\text{odd } l).$$

We will retain in the equations of motion terms linear in Δ, of second order in z and z', and of third order in ρ and ρ', obtaining the expanded orbit equations

$$\rho'' + \tfrac{1}{2}\rho = \Delta(1 + 3\rho/2) - (1 - \Delta)\beta\rho^2$$
$$+ \tfrac{1}{2}(1 + 3\Delta)\rho'^2 + (1 - \Delta)(\beta - \tfrac{1}{4})z^2$$
$$- \tfrac{1}{2}(1 - \Delta)z'^2 + (1 - \Delta)(\tfrac{1}{2} - 2\beta - \gamma)\rho^3$$
$$- \left[2 - \frac{3}{2}(1 - \Delta)\right]\rho\,\rho'^2 + \cdots$$
$$z'' + \tfrac{1}{2}z = \tfrac{1}{2}\Delta z + (1 - \Delta)(2\beta - 1)\rho z$$
$$+ (1 + \Delta)\rho' z' + \cdots.$$

To optimize β and γ, for $\Delta = 0$, we will deal only with trajectories symmetric about $\theta = 0$. A point source and its image will thus be symmetrically arranged with respect to the magnet in every order calculated. The solution for this case, obtained by iteration, is

$$\rho(\theta) = \rho_m \cos\psi + (\rho_m^2/12)[3(1 - 4\beta)(1 - \cos\psi)$$
$$+ (1 + 4\beta)(\cos 2\psi - \cos\psi)]$$
$$+ \rho_m^3\left\{\frac{1}{32}\left[\left(\frac{9}{4} - 4\beta - 2\gamma\right)\right.\right.$$
$$- \frac{1}{3}(1 + 2\beta)(1 + 4\beta)\left.\right](\cos\psi - \cos 3\psi)$$
$$+ \frac{1}{6}(1 - 2\beta)(1 - 4\beta)(\cos\psi - 1)$$
$$+ \frac{1}{18}(1 - 2\beta)(1 + 4\beta)(\cos\psi - \cos 2\psi)$$
$$+ \frac{1}{8}\left[3(1 - 4\beta - 2\gamma) - \frac{5}{4}\right.$$
$$\left.\left. + \frac{1}{3}(1 - 10\beta + 40\beta^2)\right]\psi\sin\psi\right\} + O(\rho_m^4),$$

where $\psi \equiv 2^{-\frac{1}{2}}\theta$ and ρ_m is the displacement at $\theta = 0$. This function will later be joined to a solution obtained separately in the region of fringing field in order to optimize β and γ.

To discuss dispersive effects arising from small but finite Δ, it will be necessary to consider trajectories that are not symmetric about $\theta = 0$. Here, however, we will be content with second order terms in ρ. Let ρ_i and ρ_i' be the displacement and its derivative at an arbitrary initial value θ_i. Then for $z \equiv 0$ we obtain by iteration

$$\rho(\theta - \theta_i) = \rho_i\cos\psi + 2^{\frac{1}{2}}\rho_i'\sin\psi + 2\Delta(1 - \cos\psi)$$
$$+ \Delta\left\{-(1 - 4\beta)\rho_i\right.$$
$$+ \left(\frac{3}{2} - 4\beta\right)\left[\rho_i\psi\sin\psi - 2^{\frac{1}{2}}\rho_i'(\psi\cos\psi - \sin\psi)\right]$$
$$- \left(\frac{1 + 4\beta}{3}\right)\left[\rho_i(\cos 2\psi - \cos\psi)\right.$$
$$\left.\left. + 2^{\frac{1}{2}}\rho_i'(\sin 2\psi - 2\sin\psi)\right]\right\}$$
$$+ \left(\frac{1 - 4\beta}{4}\right)(\rho_i^2 + 2\rho_i'^2)(1 - \cos\psi)$$

$$+\left(\frac{1+4\beta}{12}\right)(\rho_i^2 - 2\rho_i'^2)(\cos 2\psi - \cos\psi)$$

$$+\left(\frac{1+4\beta}{6}\right)2^{\frac{1}{2}}\rho_i\rho_i'(\sin 2\psi - 2\sin\psi)$$

$$+\left(\frac{1+4\beta}{3}\right)2^{\frac{1}{2}}\rho_i\rho_i'(\sin 2\psi - 2\sin\psi)$$

$$+ O(\Delta\rho_i^2, \rho_i^3),$$

where

$$\psi \equiv 2^{-\frac{1}{2}}(\theta - \theta_i).$$

To study the influence of displacements in z on the focal properties with respect to ρ, we may add to the foregoing equation those terms of second order in z_i and z_i', and independent of Δ, which arise from iterating the coupled equations for ρ and z through second order. These added terms appear on the right side as

$$z_i^2\left[(\beta - \tfrac{1}{2})(1 - \cos\psi) - \frac{\beta}{3}(\cos 2\psi - \cos\psi)\right]$$

$$-2^{\frac{1}{2}}z_iz_i'\frac{2\beta}{3}(\sin 2\psi - 2\sin\psi)$$

$$+ z_i'^2\left[(2\beta - 1)(1 - \cos\psi) + \frac{2\beta}{3}(\cos 2\psi - \cos\psi)\right].$$

The results obtained above agree with the second order formulas of Shull and Dennison[3]) for the special case $\psi = \pi$, $\Delta = 0$ and with the results of Svartholm[4]) for the special case $\rho_i = z_i = \Delta = 0$ in the absence of his electric field but for arbitrary ψ.

4. The Fringing Region

To discuss fringing we employ a separate Cartesian coordinate system in and beyond each fringing region. In what follows we refer explicitly to the image side; quantities referring to the source side are related to these by obvious changes of sign; for $\Delta = 0$ the trajectories from a point source are completely symmetrical about the plane $\theta = 0$. The Cartesian and cylindrical z coordinates coincide. The origin of Cartesian coordinates is at

$$r = R,\ \theta = \frac{\pi}{2} - b.$$

The y axis is directed radially outwards in the plane $z = 0$, and the x axis is directed so that particles move with increasing x. Displacements and slopes of trajectories will be matched between polar and Cartesian systems along the y axis, which separates their domains of applicability. The same unit of length will be adopted in these systems so that, at

$$\theta = \frac{\pi}{2} - b, \quad \text{where} \quad x = 0,$$

we have

$$\rho = y \text{ and } \frac{\rho'}{1+\rho} \equiv \frac{dr}{r\,d\theta} = y' \equiv \frac{dy}{dx}.$$

Both b, the angle between the y axis and the magnet edge, and a, the field fall-off distance, are of the order of the physical separation D of the magnet poles at $r = R$.

The rigorous trajectory equation for particles in the plane $z = 0$ having $\Delta = 0$ may be written in Cartesian coordinates as

$$\frac{d}{dx}\left[y'/(1+y'^2)^{\frac{1}{2}}\right] = -h(x, y),$$

where $h(x, y) = H_z(x, y)/H_0$. Now we assume that the fringing may be characterized by a single function $h(x)$ multiplied by the radial shape factor $(1 - \frac{1}{2}y + \beta y^2)$; this assumption contains two approximations which are believed to lead to negligible error but which could be corrected, if fringing field measurements showed it to be necessary: the factorization approximation seems to describe the empirical variation with gap height to within a few percent, while variations in the orientation of the axes within the small angle b seem to lead to effects of higher order than those considered here.

Under this assumption we integrate once to obtain

$$y'/(1+y'^2)^{\frac{1}{2}} = \rho/[(1+\rho)^2 + \rho'^2]^{\frac{1}{2}}$$

$$-(1 - \tfrac{1}{2}\rho + \beta\rho^2)f(x) + \tfrac{1}{2}\rho' g(x),$$

[3]) F. B. Shull and D. M. Dennison, Phys. Rev. **71** (1947) 681, Eqs (25) and (26), as corrected in Phys. Rev. **72** (1947) 256.

[4]) N. Svartholm, Arkiv f. Fys. **2** (1950) 195.

where

$$f(x) \equiv \int_0^x h(x')\mathrm{d}x' \quad \text{and} \quad g(x) \equiv \int_0^x x'h(x')\mathrm{d}x'.$$

Before integrating the right side, we have approximated $y(x)$ by $\rho + \rho' x$ in the linear term, and y^2 by ρ^2. In these and the following equations ρ and ρ' are evaluated at the matching lines $x = 0$. We next solve this equation or y' by iteration and expand in powers of ρ and ρ', obtaining

$$y'(x) = \rho'(1 - \rho + \rho^2) - \Big(1 - \tfrac{1}{2}\rho + \beta\rho^2 - \frac{3}{2}\rho'^2\Big)f - \Big(\frac{3}{2}\rho' - 3\rho\rho'\Big)f^2 + \tfrac{1}{2}\rho' g - \tfrac{1}{2}f^3 + \cdots.$$

Integrating once more, we have

$$y(x) = \rho + \rho'(1 - \rho + \rho^2)x - \Big(1 - \tfrac{1}{2}\rho + \beta\rho^2 + \frac{3}{2}\rho'^2\Big)\int_0^x f\,\mathrm{d}x + \Big(\frac{3}{2}\rho' - 3\rho\rho'\Big)\int_0^x f^2\,\mathrm{d}x + \tfrac{1}{2}\rho'\int_0^x g\,\mathrm{d}x - \tfrac{1}{2}\int_0^x f^3\,\mathrm{d}x + \cdots.$$

The optic axis $y_{\mathrm{OA}}(x)$ is obtained by setting $\rho = \rho' = 0$. The paraxial focal point x_0 is obtained by setting $y(x_0) = y_{\mathrm{OA}}(x_0)$ and retaining only the terms linear in ρ_m; the field shape parameters $\beta, \gamma, \ldots$ may be selected by requiring $y(x_0) = y_{\mathrm{OA}}(x_0)$ to higher orders in ρ.

Since $h(x)$ is negligible at $x \approx x_0$ the integrals involved may be expressed as

$$\int_0^x f(x')\mathrm{d}x' = C_1 a x + C_2 a^2;$$

$$\int_0^x f^2\,\mathrm{d}x = C_1^2 a^2 x + \mathrm{O}(a^3); \qquad x >> a$$

$$\int_0^x g(x')\mathrm{d}x' = C_3 a^2 x + \mathrm{O}(a^3),$$

with shape dependent coefficients C_1, C_2, and C_3 of order unity. Integration by parts shows that $C_2 = -C_3$; since in this paper we retain only terms of first order in a, C_2 and C_3 will not appear in the present results for β and γ.

Theoretical studies[5]) for plane parallel poles and experimental measurements[6]) on various magnets have shown that the fringing field may be roughly described by a decreasing exponential

$$h(s) \approx \begin{cases} 1 & s < -b \\ \exp\,[-(s-b)/a] & s > -b. \end{cases}$$

The approximate expression does not apply in a very small region near $s = -b$, where the sharp corner of the approximate formula must actually round off smoothly. For large distances, the already weak field actually decays somewhat slower than exponentially. Here s is the distance measured outward from the pole edge; in our coordinate system it would be replaced by $x + b$. While for orientation one could adopt this exponential x dependence for the slanted poles, we have preferred to evaluate $C_1 a$ by numerical integration of a typical fringing field, taking $b = \frac{1}{2}D$, and obtaining $C_1 a \approx (4/3)D$. Careful measurements of the actual fringing field of a completed instrument could be used to refine this value of $C_1 a$, to examine the validity of the fringing assumptions made above, and to determine $C_3 a^2$. This information could then be used as a guide in making minor pole tip changes in the fringing region if necessary.

5. Evaluation of β and γ

Using the forms defined above for the fringing integrals, we may write

$$y(x_0) - y_{\mathrm{OA}}(x_0) = \rho + \Big(-\tfrac{1}{2}\rho + \beta\rho^2 + \frac{3}{2}\rho'^2\Big)C_3 a^2 + [\rho' - \rho\rho' + \rho^2\rho' - \Big(-\tfrac{1}{2}\rho + \beta\rho^2 + \frac{3}{2}\rho'^2\Big)C_1 a + \Big(\frac{3}{2}\rho' - 3\rho\rho'\Big)C_1^2 a^2 + \tfrac{1}{2}\rho' C_3 a^2]\,x_0 + \mathrm{O}(a^3,\ \rho^3 a,\ \rho^4).$$

Here $\rho = \rho_0 + \rho_1 + \rho_2$, $\rho' = \rho_0' + \rho_1' + \rho_2'$, (where ρ_0 is of order ρ_m, ρ_1 of order ρ_m^2, etc.) are obtained from the first trajectory solution given in section 3 and its derivative, and are evaluated at $\theta = \frac{1}{2}\pi - b$. Expanding in powers of ρ_m, we obtain first

[5]) N. D. Coggeshall, J. App. Phys. **18** (1947) 855.

[6]) *E.g.*, C. Mileikowsky, Arkiv f. Fys. **7** (1953) 33 fig. 2, and unpublished measurements by C. Dols at this laboratory.

$$0 = \rho_0(1 - \tfrac{1}{2}C_3a^2) + \{\rho_0'[1 + \tfrac{1}{2}(C_3 + 3C_1^2)a^2] + \tfrac{1}{2}\rho_0C_1a\}x_0;$$

hence

$$x_0 = d[1 + \tfrac{1}{2}C_1da - \tfrac{1}{4}(6 - d^2)C_1^2a^2 + \cdots],$$

where

$$d \equiv -\rho_0/\rho_0' = 2^{\frac{1}{2}}\cot 2^{-3/2}(\pi - 2b)$$

is the distance from focal point to the joining line if the fringing integrals vanish. We next evaluate y_{OA} at the focal point, obtaining

$$y_{OA}(x_0) = -C_1ax_0 + C_3a^2 + O(a^3),$$

which displays the additional bending of the optic axes due to fringing.

Terms of the next order in ρ_m, when collected, yield

$$\frac{\rho'}{\rho_0} - \frac{\rho_1'}{\rho_0'} + \rho_0[1 - (\beta + \tfrac{3}{4}\tan^2\psi)C_1da] + O(a^2) = 0.$$

The terms in this equation which are independent of a determine β_0; those linear in a fix β_1, etc. We have for β_0 the equation $\rho_1 + d\rho_1' = -\rho_0^2$, where from section 3

$$\rho_0 = \rho_m\cos\psi, \qquad \rho_0' = 2^{-\frac{1}{2}}\rho_m\sin\psi,$$

$$\rho_1 = (\rho_m^2/12)[3(1 - 4\beta)(1 - \cos\psi) + (1 + 4\beta)(\cos 2\psi - \cos\psi)],$$

$$\rho_1' = 2^{-\frac{1}{2}}(\rho_m^2/12)[3(1 - 4\beta)\sin\psi - 2(1 + 4\beta)(\sin 2\psi - \sin\psi)].$$

Substituting and solving for β_0 we obtain

$$\beta_0 = \tfrac{1}{4}\frac{7 + 5\cos 2\psi}{5 + \cos 2\psi},$$

where $2^{\frac{1}{2}}\psi = \tfrac{1}{2}\pi - b$, and would be $\tfrac{1}{2}\pi$ in the absence of fringing. If we repeat, retaining terms linear in a, we obtain $\beta = \beta_0 + \beta_1a + O(a^2)$, with

$$\beta_1 = -\frac{3}{2}\frac{1 + \cos 2\psi}{5 + \cos 2\psi}\left(\beta_0 + \frac{3}{4}\tan^2\psi\right)C_1d.$$

In a similar manner one could evaluate β_2 if desired.

In collecting terms of third order in ρ_m to evaluate γ we will, as explained earlier, retain only those independent of a, leading to an evaluation of γ_0 but neglecting γ_1. This equation is

$$\rho_2 + d\rho_2' = -2\rho_0\rho_1.$$

After substituting, rearranging terms, and separating those involving γ_0, the equation is

$$\frac{\gamma_0}{8}(9\cos\psi + \cos 3\psi + 6\psi/\sin\psi) + \frac{1}{18}(7 - 34\beta + 40\beta^2) + \left(-\frac{231}{192} + \frac{113}{24}\beta - \frac{7}{6}\beta^2\right)\cos\psi + \left(\frac{5}{18} - \frac{7}{9}\beta + \frac{4}{9}\beta^2\right)\cos 2\psi + \left(-\frac{39}{192} + \frac{1}{24}\beta + \frac{1}{6}\beta^2\right)\cos 3\psi + \left(-\frac{25}{96} + \frac{23}{12}\beta - \frac{5}{3}\beta^2\right)(\psi/\sin\psi) = 0.$$

Numerical values for β_0, β_1, and γ_0 will be presented in section 7.

6. Dispersion

To determine the linear dispersion properties of the field we neglect fringing effects and examine those terms of the solution found in section 3 for $\Delta \neq 0$ which are of order ρ, Δ, and $\rho\Delta$. We now regard $2^{\frac{1}{2}}\psi_i = -\pi/2$ as the point of entry into the magnet and $2^{\frac{1}{2}}\psi_f = \pi/2$ as the point of exit. If a point source is located on the optic axis a distance d_0 from the magnet, the particles will travel in straight lines to the pole edge where their displacement and slope will be related by $\rho_i = d_0\rho_i'$. By inserting this relation into the terms to be studied and their derivatives, we obtain the displacement and slope of a trajectory at any angle inside the magnet. We evaluate these expressions at the point of exit and, after some reduction, obtain

$$\rho_e = \rho_i(1 + \alpha_1\Delta/d_0) + \alpha_0\Delta,$$
$$\rho_e' = -\rho_i'(1 - \bar{\alpha}_1\Delta d_0/2) + \alpha_0\Delta d_0/2,$$

where

$$\alpha_0 = 2(1 - \cos 2\psi_f),$$

$$\alpha_1 = 2^{\frac{1}{2}}\left[\frac{3}{2}(2\psi_f + \sin 2\psi_f) + 4\beta(\sin 2\psi_f - 2\psi_f)\right],$$

$$\bar{\alpha}_1 = \alpha_1 + (4/3)(1 + 4\beta)(1 - \cos 2\psi_f)/d_0.$$

The trajectories after leaving the magnet are straight lines whose equations are $y = \rho_e' x + \rho_e$, or $y - y_0 = \rho_e'(x - x_0)$, where y_0 and x_0 are the coordinates of the paraxial image, and depend linearly on Δ. An elementary calculation yields

$$y_0 = \alpha_0 \left(1 + \frac{d_0^2}{2}\right)\Delta = 4\Delta,$$

or the linear dispersion $y_0/\Delta = 4$, as expected for any symmetrical instrument. For finite Δ the image is also displaced in x, by the amount

$$x_0 - d_0 = (\alpha_1 + \tfrac{1}{2} d_0^2 \bar{\alpha}_1)\,\Delta.$$

The focal plane for paraxial rays is obtained by eliminating Δ between these two equations, and is not normal to the optic axis, but is turned in the sense of increasing θ through an angle ϕ from this position;

$$\tan \phi = \tfrac{1}{4}\,(\alpha_1 + \tfrac{1}{2}\, d_0^2 \bar{\alpha}_1).$$

Aberrations due to terms of order ρ^2 will not vanish for $\Delta \neq 0$, but will produce a cross-fire of trajectories leading to images of finite radial extent. These will not lie in the focal plane obtained above, but in a curved focal surface tangent to this plane at the image point for $\Delta = 0$. Estimates, not to be presented here, indicate that for large radial apertures the range of momenta in good focus is quite small.

7. Numerical Results

The spectrometer of Asaro and Perlman at this laboratory has been designed with $R = 35$ cm; the pole gap DR at this radius is 2.54 cm, so that $D = 0.0726$. Having chosen $b = \frac{1}{2}D$, we use $2^{\frac{1}{2}}\psi = \frac{1}{2}\pi - 0.0363$, to calculate $\beta_0 = 0.236$, and $\beta_1 a = -0.032$, where we have inserted $C_1 a = (4/3)D$. We thus obtain $\beta \approx 0.204 + O(a^2)$. The actual value chosen for this instrument was $\beta = 0.209$, based on estimates of the neglected terms, although this difference amounts to a change in field strength of only about 0.05 % for $|\rho|$ as large as 0.3. Using this value of β, but inserting $\psi = 2^{-3/2}\pi$, we calculate $\gamma_0 = -0.15$. An uncertainty in γ of 0.04 corresponds to a change in field strength of 0.1 % for $|\rho|$ as large as 0.3; just as $\beta_1 a$ is an eighth of β_0, one might expect $\gamma_1 a$ to be an order of magnitude smaller than γ_0, so that the neglected terms correspond to higher accuracy than can be attained in field shaping. Terms higher than the third order have not been considered; their effects are difficult to predict and should perhaps already be considered for this large an aperture.

The angle of rotation ϕ of the paraxial focal plane, calculated using the full sector angle, is found to be $\tan^{-1} 1.78 \approx 60°$.

The neglect of detailed calculations of motion in z requires justification here. The terms quadratic in z_i and z_i' given in section 3 have been evaluated for $z_i = d_0 z_i'$ and extrapolated into the image space, where they produce a radial spread of the image. This spread is of order $[2^{-3/2} D \sin (2^{-3/2}\pi)]^2$, is extremely small for the small D used here, and contributes a negligible amount to the image size. The resolution of the instrument will therefore be determined primarily by the source size and by residual magnetic field errors. The image height can be estimated from the terms of order ρz in the z equation of motion, and is of order 0.1 cm for the parameters used above.

The solid angle accepted by the magnet is approximately $\frac{1}{2}\rho_m D \sin^2 2^{-3/2}\pi$, which is 0.017 steradians for $\rho_m = 0.3$ and the D used above.

Preliminary measurements on this spectrometer have indicated a resolution of 0.1 % in energy with a solid angle of about 0.009 steradians.

The authors are grateful to Dr. Asaro for many helpful discussions and for unpublished performance data, and to Mr. James Baker for extensive assistance with the calculations. This work was performed under the auspices of the United States Atomic Energy Commission.

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EVAPORATION DEVICE FOR BETA-SPECTROMETER SAMPLES

R. STOCKENDAL and K. E. BERGKVIST

Nobel Institute of Physics, Stockholm 50, Sweden

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The construction of the evaporation crucibles described below, is a result of attempts to obtain radioactive samples with the activity concentrated on a very small area. This is necessary in some cases, for instance when the sample is to be used for measurements in spectrometers with high resolution. The apparatus has been used at the Nobel Institute of Physics for preparation of samples for beta-spectrometers of various kinds.

The crucibles, two examples of which are shown in fig. 1, have been given a form which can focus the beam of radioactive atoms onto a small area. The dimensions are such as to give the highest temperature in the middle part of the device during the evaporation, performed by heating with an electric current (cf. fig. 1c). The crucibles, made of platinum and soldered with a platinum hard-solder can stand a temperature of 1600° C.

Samples for a permanent magnet beta-spectrometer for photographic recording[1]) have been prepared by use of the crucible shown in fig. 1a, with the activity evaporated onto a wire (Pt or Cu) of 0.2 mm diameter. A similar crucible with a 0.6 mm slit has been used for preparation of samples of rectangular shape on thin foils (usually Al) for use in a double-focusing beta-spectrometer[2]). The conical crucible, shown in fig. 1b, has been used for preparation of circular samples of ca. 2 mm diameter on thin foils (usually Al) for use in an intermediate-image beta-spectrometer[3]). The activities used so far have consisted of $TlCl_3$, $PbCl_2$ and $BiCl_3$.

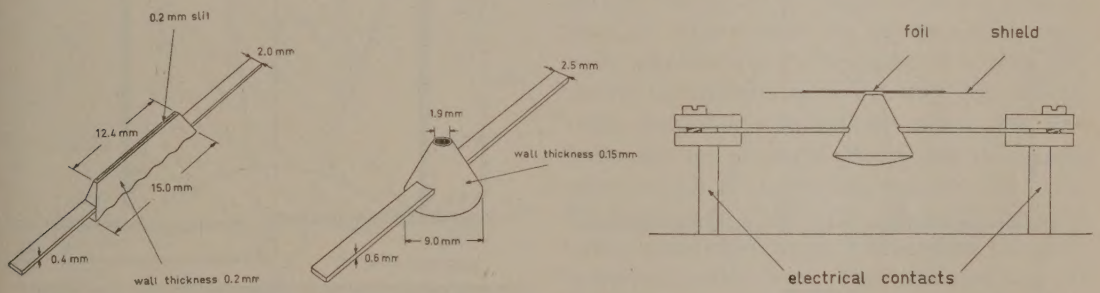

Fig. 1. a. Crucible for evaporation onto a wire (50 — 65% yield on a 0.2 mm wire). b. Crucible for preparation of circular samples on a foil (80 — 90% yield on a circular area with 1.9 mm diameter). c. Set-up of evaporation device

The active solution (smallest possible volume) can be transferred to the crucible with a small glass pipette. During this procedure the crucible is heated with a small electric current in order to dry the liquid. The corrugated form of the bottom of the crucible shown in fig. 1a prevents

[1]) H. Slätis, Arkiv Fysik 6 (1953) 415.

[2]) A. Hedgran, N. Svartholm, and K. Siegbahn, Proc. Phys. Soc. A **63** (1950) 960.

[3]) H. Slätis and K. Siegbahn, Arkiv Fysik **1** (1949) 339

the solution from running towards the ends during this procedure. After placing the sourceholder with a wire or a foil as near as possible above the crucible (ca. 0.1 mm for a wire and ca. 0.4 mm for a foil), the evaporation is made under vacuum by a short glowing with a current of 30–45 Amps generally used for our evaporations, i.e. ca. 0.1 mm for the crucible of fig. 1a and ca. 0.4 mm for the conical crucible of fig. 1b. No shielding plate was in this case placed between the crucible and the foil. By measuring the activity of each foil, the distribution curves of fig. 2 were obtained.

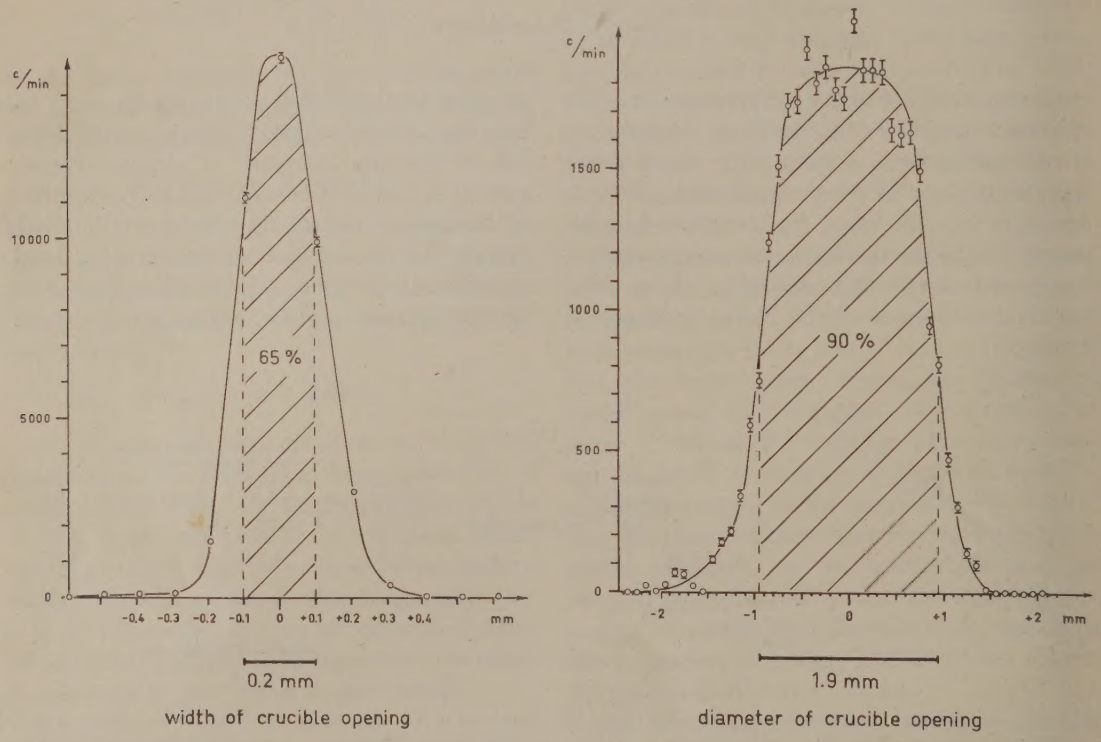

Fig. 2. a and b. Curves showing the distribution of activity evaporated by use of the crucibles shown in figs. 1a and 1b respectively. The shaded areas indicate the yields on areas of the same size and form as the openings of the crucibles

(cf. fig. 1c). The time of glowing should be limited to one or two seconds to give maximum yield.

An investigation was made with the two crucibles shown in fig. 1 in order to find the distribution of evaporated material. For this purpose radioactive $BiCl_3$ was evaporated onto a smooth surface formed by the upper edges of closely packed Al foils, each of 0.1 mm thickness. The distance between this surface and the opening of the crucible was the same as is The figure indicates for each crucible the yield of evaporated material on an area of the same size and form as the opening of the crucible. It is easily calculated that for this area the crucible of fig. 1a, designed for evaporations onto a wire, gives about 65 % yield (see fig. 2a), while the conical crucible of fig. 1b gives a yield of about 90 % (see fig. 2b). These values are in agreement with those found in preparations of actual samples: 50–65 % and 80–90 % respectively.

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DIVERGING ELECTROSTATIC LENSES IN ACCELERATORS

E. BREITENBERGER

Department of Physics, University of Malaya, Singapore 10

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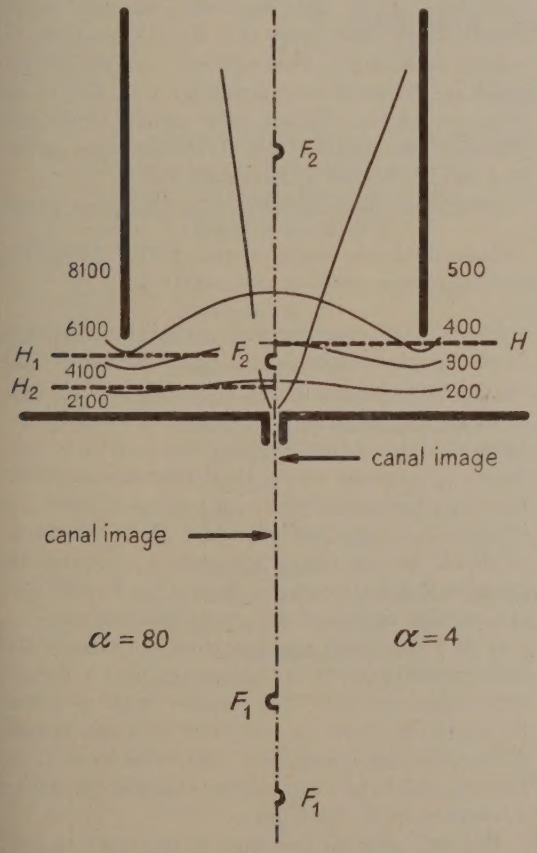
Most electron-optical lenses are converging. A notable exception occurs in particle accelerators where the ions emerge through a narrow canal in a plate into an accelerating column. The diverging properties of this plate-to-cylinder lens are not always taken advantage of, nor have they been exhaustively discussed in the literature; a brief indication of some essentials may thus be useful.



The figure exemplifies the situation for a plate-to-cylinder distance of one-half the cylinder radius. The field was calculated by relaxation; three of the equipotentials are shown. The lens performance depends only on the voltage ratio $(V'' - V')/V' = \alpha$, as usual. The foci and principal points were found graphically for $\alpha = 4$ and 80, and are indicated in the right and in the left half of the figure, respectively. To fix the ideas, let $V' = 100$ volts, representative of the particle energy at the outlet of an r–f or magnetic ion source; then the equipotentials have to be numbered as in the figure. It is seen that raising the cylinder potential from 500 to 8100 volts does not substantially affect the first focus, nor the principal planes, but the second focus is shifted appreciably towards the plate. The result is that the virtual image of the canal outlet which the lens produces behind the plate is thrown farther back. Thus the emerging ion beam becomes less divergent; it can never become convergent, though, and "blow up" before it reaches the next accelerating stage.

Actual trajectories are shown for an ion which emerges under an angle of 30° with respect to the axis; their shape indicates that the Seidel aberrations of the lens are not so large as to impair the value of gaussian image construction very seriously for the practical case of ions emerging under much smaller angles.

Letting the canal protrude over the plate will increase the curvature of the equipotentials, and thereby increases the power of the lens. Of course, a protruding canal also has the advantage that space charges and gas are sucked away more rapidly. On the other hand, it would appear to be bad practice to mount the canal outlet in a recess of the plate.

BOOK REVIEWS

Reports on Progress in Physics, Volume XIX (1956) (The Physical Society, London 1956, 367 pages price to non-fellows £ 2 10 s., to fellows, one copy, £ 1 7 s 6 d).

This volume contains nine different survey articles dealing with recent progress in various fields of modern physics. G. H. A. Cole reviews the theory of liquids and demonstrates the considerable improvments that have been made during the past few years. For the readers of this journal the article by J. D. Blewett on proton synchrotrons should be of particular interest. After a brief survey of proton electrodynamics in the conventional synchrotron the author gives an interesting compilation of and comparison between characteristic design parameters of the various proton synchrotrons including the 10 GeV Canberra air-cored synchrotron project. Finally the article contains short discussion of the fixed field alternating gradient (FFAG) principle for the acceleration of charged particles. The methods based on radioactive decay for determining geological age are excellently reviewed by L. M. Ahrens. Other contributions deal with infra red absorbtion in semiconductors (H. Y. Fan), "Aero-Thermoacoustics" i.e. the generation of sound by turbulence and by heat processes (O. K. Mawardi) and the application of diffraction theory to the study of the ionosphere. J. H. Tait discusses some aspects of neutron diffraction theory that are of importance in reactor technology. Developments in geometrical optics are discussed in an article by C. G. Wynne on New Lens Systems. Finally, some aspects on thermodynamics are reviewed in R. O. Davies paper on the Macroscopic Theory of Irreversibility.

The new volume is an excellent sequel to this series.

T. R. GERHOLM

ARTHUR HOLLY COMPTON, *Atomic Quest*, (Oxford University Press, 370 pages, 30 s.).

This new book about the atomic bomb is written by one of those in highest responsibility during the war and is therefore a tribut to the history of World War II. The author has made it his task to focus the attention on the scientists who developed the fission bomb. As far as the general development goes the book covers the same material as the Smyth report, though concentrating on and enlarging the story of the plutonium project because this was the authors prime concern during the war. The first three chapters deal with the scientific background, the achievement of the controlled fission reactor, and finally the manufacture of the bomb.

In the fourth chapter Compton takes up a discussion about the decision to use the bomb against Japan. Compton was himself a member of the Scientific Panel appointed to advise the Interim Committee which had to recommend the course of action. On the controversial matter about the use of the bomb, Compton's firm point of view is that the intention behind its use was to shorten the war and gain a net saving of lives. He gives proofs in the form of citations that its effect was such as to help Japan to surrender earlier than otherwise would be the case. Compton's views on various matters are influenced by his Christian belief. With this background he gives in the last chapter an account of his views on war, peace, and freedom in the Atomic Age. His opinion is that atomic weapons have come to stay and that their presence does not change the basic morality of war. A "major war must be fought with atomic weapons", but considering the situation he continues "war (is) unlikely between nations ready with atomic weapons". His belief seems to be that by social and technological changes war will in a few decades be ruled out.

The well selected headings of the five chapters are; Vision, Faith, Work, Choice, and Hope.

G. EKSPONG